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FINAL TECHNICAL REPORT

OCTOBER 1995

## SAMPLE ACQUISITION & INSTRUMENT DEPLOYMENT

ORIGINAL CONTAINS  
COLOR ILLUSTRATIONS

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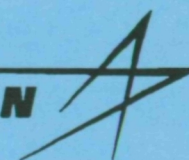
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Contract NASW-4818

**FINAL TECHNICAL REPORT**  
**FOR THE**  
**SAMPLE ACQUISITION & INSTRUMENT DEPLOYMENT**  
**(SAID)**  
**OCTOBER 1995**

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## **FOREWORD**

This document was prepared in accordance with the requirements of NASA Contract NASW-4818, Section F.6(b), Final Report.

## Introduction

This report details the progress for contract NASW-4818, Sample Acquisition and Instrument Deployment (SAID), a robotic system for deploying science instruments and acquiring samples for analysis. The system was developed on the Planetary Instrument Definition and Development Program (PIDDP). The progress reported is for the period October 1993 through October 1995. Significant progress has been made in the following areas:

### • Systems Design:

A baseline design has been achieved through analysis and trade studies of position sensors, motors, gear trains, brakes, shape memory alloys. The design considers environmental operating conditions on the surface of Mars, as well as volume constraints on proposed Mars Landers. Control issues have also been studied, and simulations of joint and tip movements have been performed.

### • Wrist Development:

A passively braked shape memory actuator with the ability to measure load has been developed. The wrist also contains a mechanism which locks the lid output to the bucket so that objects can be grasped and released.

### • Wrist Testing:

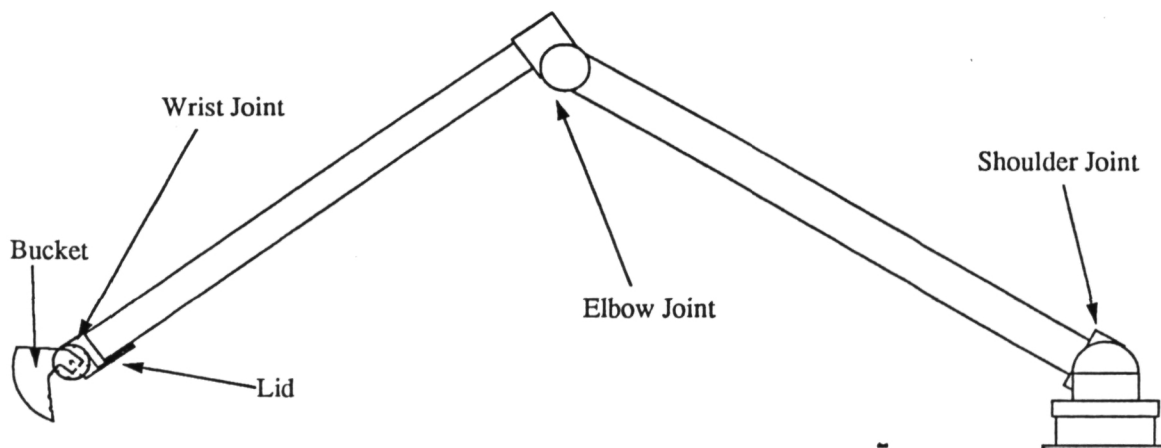
The wrist actuator has been tested for operational power and mechanical functionality at Mars environmental conditions. The torque which the actuator can produce has been measure. Also, testing in Mars analogous soils has been performed.

### • Elbow and Shoulder Joint Development:

Dry lubricated harmonic drive gears, and step motors have been utilized in a joint design which can accommodate operation at extremely cold temperatures. Resolvers are used for position feedback. Electronics and software for controlling multiple joints has also been developed. A complete 3-DOF SAID system has been assembled for testing.

### • Elbow and Shoulder Pitch Joint Testing:

The arm has been tested for positioning control, and movements requiring coordination of two joints to move the tip along a straight line path using resolver information and developed software and electronics. Functional tests such as digging and lifting were performed and video taped. The elbow joint was successfully operated in a thermal vacuum chamber at temperatures down to  $-80^{\circ}\text{C}$ .



**Figure 1** SAID is a conventional arm with 4 degrees of freedom, and 2 meter length.



## **Systems Design**

The most significant future opportunities for a sample acquisition and instrument deployment system are missions to the surface of Mars, although Lunar mission may also find the system beneficial. Design of the SAID system would take Mars environment factors into consideration, and draw on past studies, scheduled and proposed missions to the surface of Mars for functional requirements.

The surface of Mars is cold with equatorial temperature ranging from 205-225°K and polar temperatures of 200°K day time and 150°K for polar night time. The mean surface pressure is 6.1 mb, with a composition of 95% CO<sub>2</sub>. Mars is generally 20 times dustier than Earth with global and local dust storms. Dust storms are estimated to raise the number of dust particles/cm<sup>3</sup> in the atmosphere near the surface to ~30 from a typical value of ~2.

SAID system design is intended to satisfy requirements for operation from a MESUR Pathfinder type of lander, where the shoulder is mounted close to the ground. The first limb of arm extends upward and out from the shoulder 1 meter ( see Fig. 1). The second limb connected by the elbow joint reaches back downward 1 meter, allowing the manipulator to reach over objects. This conventional arm style is generally heavier than the SCARA arm configuration which does not have the ability to reach over objects. This is also useful when operated from an elevated shoulder position such as a Viking style lander or Mars rover. Studies of the stowage configurations and volume needed for SAID onboard a MESUR Pathfinder type lander and a Mars '98 soft lander have been studied, and appear to be realistic.

Torque and positioning requirements for the SAID system have been driven by mass estimates of various instruments which have been proposed, and estimates of the Martian soil properties and the forces needed to dig in them effectively. Instruments benefiting from a SAID manipulator are listed below.

### **Instruments Requiring Soil Samples**

Differential Thermal Analyzer (DTA)  
Thermal Evolved Gas Analyzer (TEGA)  
X-ray Fluorescence (XRF)  
Mars Aqueous Chemistry (MACE)  
X-ray Diffraction (XRD)

### **Instruments Which Can Be Deployed**

Alpha Proton X-ray Fluorescence (APX)  
Seismometer  
Ground Penetrating Radar antenna (GPR)  
Camera, Stereo or Multispectral  
Rock drill, grinder or chipper

## **Selection of Upper-Arm Actuators**

The nature and configuration of the drive systems of the various joints is fundamental to the capability of the arm. Operation in the cold Martian atmosphere plays a fundamental roll in the selection of actuators for the various joints.

For most 3 of the 4 degree's of freedom DC brushless motors with large gear reduction ratios of ~1000:1 seem to best fulfill the torque and positioning requirement. However, operation in the cold environment presents a problem for the gear reduction.

Unlike the bucket, the upper arm (i.e., the shoulder through the elbow) requires coordinated motion of three joints and relatively large torques, especially when an instrument is being carried at the end of the extended arm. Torques up to approximately 24 N-m (18 ft-lbf) are required at the shoulder pitch joint and up to 11 N-m (8 ft-lbf) at the elbow pitch joint to accelerate a 0.75 kg (1.7 lb) instrument upward in Martian gravity. Speed of motion is not a large issue. Baseline goals are for motion up to about 1.25 cm/s (0.5 in/s).

A variety of actuators can satisfy these requirements, but they differ in cost, size, weight, efficiency, compatibility with the Martian polar environment, and other relevant factors. Actuators commonly used in robotics and related applications include brushless and brush-type dc motors, ac motors, stepper motors, linear and rotary hydraulic actuators. Table 2 summarizes how these actuators compare in satisfying several evaluation criteria.

**Table 2 - Actuator Selection Trade off Table.**

| Criterion                              | Weight | Brushless DC | Brush-type DC | AC  | Step Motor | Linear Hydraulic | Rotary Hydraulic |
|----------------------------------------|--------|--------------|---------------|-----|------------|------------------|------------------|
| Cost, Including Drive Elec.            | 10     | 7            | 10            | 5   | 10         | 3                | 3                |
| Weight and Size, Including Drive Elec. | 9      | 6            | 7             | 5   | 10         | 2                | 2                |
| Life and Environment Compatibility     | 8      | 7            | 5             | 10  | 10         | 1                | 1                |
| Power Consumption / Efficiency         | 6      | 10           | 10            | 7   | 5          | 5                | 5                |
| Ease of Use in Feedback Control        | 4      | 10           | 10            | 7   | 6          | 3                | 5                |
| Weighted Total Score                   |        | 280          | 303           | 245 | 324        | 98               | 106              |

The cost of the drive circuitry was also considered, and for one-of-a-kind flight hardware, the cost of such circuitry is dominated by engineering costs, which varies with circuit complexity. The stepper motor's drive circuitry is hard to beat for simplicity, as it requires only computer-controlled switches. Brush-type dc motors can be just about as simple if pulse-width modulation is used. Their drive circuitry needs a pulse-width modulator but only half the number of switches. A brushless dc motor requires 50% more switches than a brush-type motor with pulse-width modulation, and commutation circuitry must be added, so the drive electronics becomes more expensive. In addition, the Hall-effect sensors usually used for commutation can be expected to increase the cost. The ac motor requires an ac source, which increases the cost of the drive electronics. Also, pulse-width modulation schemes are not attractive with ac motors, so there is the added cost of the circuitry to vary the ac voltage in response to computer command. These factors dominate over the difference in cost of the motor itself. While hydraulic actuators need not be expensive, they require voltage-controlled or motor-operated valves and a hydraulic pumps with their own motors, which greatly reduces their attractiveness.

Size and weight similarly favor the stepper motor, and for similar reasons. The support circuitry is minimal, so drive circuitry does not add much to the total weight. AC and stepper motors were rated highest for life and environmental compatibility because they are rugged, contain no temperature-sensitive electronic parts, and have no contacts to wear out or get contaminated. The brushless dc motor has Hall-effect sensors whose operating temperature range may require some thermal control. Brush-type dc motors are subject to brush wear and contact contamination. Their life would be adversely affected by dust. Hydraulic actuators are least compatible. Normal hydraulic fluids are not suitable for the extreme cold, which also makes selection of suitable hoses or tubing difficult.

In power consumption and efficiency, dc motors perform well. However, the way the actuators are used has more to do with their overall efficiency than their inherent properties. For example, the assumption used in evaluating dc motors was that they would be used in a linear feedback control scheme employing pulse-width modulation of motor voltage, whereas steppers would be used for open-loop control. The feedback reduces drive to the dc motor to just what is required, whereas the stepper, operating open loop, gets full drive voltage at all times. This results in the stepper's being rated somewhat lower in efficiency.

Ease of use in feedback control was the last and least important evaluation criterion. Feedback control is desirable but not essential for producing accurate motion control. For this, dc motors are nearly ideal, as their output torque is readily varied with pulse-width modulation and their response is very nearly linear. For ac motors, continuous control requires more complex circuitry, and response is not generally as linear. Rotary hydraulic actuators can be made to have linear response, but the cost and complexity of driving the valves makes them less attractive. Steppers could, in principal, be used for linear feedback control but are most suitable for open-loop operation. Linear hydraulic actuators (pistons) have the disadvantages of their rotary cousins plus the problem of joint torque variation with joint angle due to the changing moment arm.

Although the precise-looking numerical results in the table reflect relatively imprecise subjective evaluations, the overall advantage of stepper motors for this application appears clear. One additional concern not mentioned is the gear reduction required for steppers vs. brushless DC motors. The stepper motors natural speed of rotation is at least 10 times slower than the brushless DC motors which makes achieving the necessary speeds of motion possible without providing gear reduction beyond what is required for achieving the needed torques.

In using steppers, it should be taken as a fact of life that steps will be missed. This means that control based purely on counting of steps of a stepper motor will eventually get "off track," so some form of absolute joint-angle sensing is required to provide periodic corrections for missed steps.

Of course actuators using feedback control would also require these sensors, the point to be noted here is that use of stepper motors does not eliminate the need for them as it might at first appear.

### **Shape Memory Actuators**

The shape memory actuator provides torque to a joint from the force of the shape memory muscle's contraction much like the muscles in a human arm. The muscle is composed of a number of strands of shape memory wire (NiTiCu Alloy) secured at each end mechanically and electrically. When power is applied the wires heat up; once their phase change temperature is reached (70°C-120°C depending on load) they undergo martensitic transformation, contracting about 3% of their length. When power is then removed the wires cool below their phase change temperature and return to their original length. At the joint end of the muscle a pulley is attached which is used as a turnbuckle to double the length which the muscle can pull. One end of the cable looped through the turnbuckle is attached to the hub to provide rotary motion; and the other end is attached to a rap spring brake trigger. When the muscle begins pulling the force on the rap spring trigger removes the braking force allowing the hub to rotate in one direction. Once the brake is release and the rap spring trigger contacts it's stop, all of the force of the muscle is transferred into the hub. Two muscles and two rap spring brakes are required for rotary motion in both directions. Also it is necessary for the working muscle to reload the other muscle to it's prestrained condition. The phase change occurs slowly enough in a multistrand muscle that the speed of the rotary motion is at a controllable level.

Shape memory metal rotary actuators developed and tested at Martin Marietta have several advantages over motor/gear drives for this application: 1) lower mass 2) no gears 3) no lubricants 4) tolerant to dust contamination 5) operates at very low temperatures 6) simple drive electronics. Disadvantages include: 1) power consumption 2) positioning control 3) volume consumed by ~80 cm muscle length.

The advantages for shape memory metal in this application are significant. The high power consumption and poor positioning control eliminate this type of actuator for use in the shoulder or elbow joints, where high torque's and accurate positioning are required. However, the wrist pitch joint requires much smaller torque's which can be achieved with reasonable power budgets. Also, positioning requirements for the wrist pitch joint are less severe, ( $\pm 1^\circ$  - wrist vs.  $\pm 0.1^\circ$  - shoulder) which we believe to be feasible with the shape memory actuator. The volume for the muscle length can be accommodated in the forearm link of the arm which will be constructed of a 6 cm diameter composite tube approximately 100 cm long.

### **Gear Reduction**

To satisfy torque and positioning requirements for the upper arm joints a large gear reduction of ~1000:1 will be required. Gear-trains being considered include spur, planetary, worm and harmonic gear sets. Planetary gears are the least compliant but have the greatest mass. Worm gear systems sized for this application have less than half the mass of planetary gears but have an order of magnitude greater backlash and compliance which would make it difficult at best to obtain the desired positioning abilities of the upper arm. Spur gears and harmonic gears are the best choice for this application. The highest ratio available in harmonic gear sets is 160:1. To reach the ~1000:1 reduction desired a spur gear with a reduction ratio of ~8:1 would be used for the input to the harmonic drive. The harmonic drive with the input spur gears and appropriate bearings saves more than 400g over a comparable drive using only spur gears. The difficulty with harmonic drives is in satisfying lubrication requirements at very cold temperatures while holding the efficiency to an acceptable level. It may be necessary to actively heat the drive before operation at temperatures below  $-10^\circ\text{C}$ . We are studying alternative lubricating techniques for the harmonic drives which will produce greater efficiencies at the cold temperatures, and hopefully eliminate the need for any active heating. We are confident that harmonic drives with small spur gear reductions on the input side will produce the most functional drive system for the upper arm joints.

### **Drive System Design**

After studying various drive systems for this application a hybrid arm seemed to make the best use of the advantages of the various types of drives while minimizing their disadvantages. Stepper motors with harmonic gear sets can best supply the high torque and tight positioning accuracy needed for the upper arm joints (elbow and shoulder). Motors will be  $45^\circ$ , bi-polar driven steppers to provide the maximum torque possible at low pulse rates and minimize wiring to the motors. Gear-trains have been selected to provide the necessary torque's and also to provide a step resolution which results in tip positioning of 1.3 - 1.1 mm with the arm fully extended. Shape memory muscles can save mass and best tolerate the cold and dusty environment, and will be used for the wrist actuator.  $1^\circ$  of motion at the wrist joint results in 1.6 mm at the tip in accuracy which we believe to be achievable with a shape memory actuator. Table 3 details the drive system components for the 4 joints being built for the SAID program.



**Table 3 - Actuators selection for SAID**

| Joint          | Angle of Motion | Actuator Torque           | Actuator Type                           | Gear Ratio and Mass                            | Motor Torque and Mass            | Actuator Mass       |
|----------------|-----------------|---------------------------|-----------------------------------------|------------------------------------------------|----------------------------------|---------------------|
| Wrist Pitch    | 180°            | 4.2 N-m<br>(3.1 ft-lbf)   | shape memory muscles                    | 1:1 ratio<br>pulley mass = 44 g                | 184 g for both muscles           | 228 g<br>(0.50 lbs) |
| Elbow Pitch    | 180°            | 16.9 N-m<br>(12.5 ft-lbf) | stepper motors, harmonic & spur gearing | HD-100:1<br>Spur-7:1<br>Total-700:1<br>287 g   | 5.9 N-cm<br>(8.4 in-oz)<br>88 g  | 357 g<br>(0.79 lbs) |
| Shoulder Yaw   | 360°            | 5.7 N-m<br>(4.2 ft-lbf)   | stepper motors, harmonic & spur gearing | HD-100:1<br>Spur-12:1<br>Total-1200:1<br>307 g | 1.1 N-cm<br>(1.7 in-oz)<br>37 g  | 344 g<br>(0.76 lbs) |
| Shoulder Pitch | 90°             | 30.8 N-m<br>(22.7 ft-lbf) | stepper motors, harmonic & spur gearing | HD-160:1<br>Spur-8:1<br>Total-1280:1<br>457 g  | 14.8 N-cm<br>(21 in-oz)<br>170 g | 627 g<br>(1.38 lbs) |

The drive systems are designed with enough stiffness that the dynamic loads expected during movement will not add so much deflection to the joint that the absolute position sensor and logic confuse the deflections with missed steps. Static deflection for the arm from shoulder and elbow pitch actuators under different load in Mars gravity are show in Table 4a. This table does not consider deflection from bearings or arm links and assumes the maximum allowed current to the motors. Table 4b summarizes vertical deflection vs. arm extension in Mars gravity while carrying a 0.75 kg load at the tip of the arm. Joint torques for the above loads varied from 10.8 N-m (8 ft-lbf) to 19.8 N-m (14.6 ft-lbf) at the shoulder and from 3.1 N-m (2.3 ft-lbf) to 8.7 N-m (6.4 ft-lbf) at the elbow.

**Table 4a - Total Actuator deflection with load.**

| Load in Bucket (kg) | Total Deflection (mm) |
|---------------------|-----------------------|
| 0                   | 1.001                 |
| 0.25                | 1.202                 |
| 0.50                | 1.394                 |
| 0.75                | 1.560                 |
| 1.00                | 1.706                 |
| 1.25                | 1.852                 |
| 1.50                | 1.987                 |

**Table 4b - Total Actuator deflection from extension carrying a 0.75 kg load.**

| Arm Extension (m) | Total Deflection (mm) |
|-------------------|-----------------------|
| 0.30              | 0.031                 |
| 0.50              | 0.089                 |
| 0.75              | 0.217                 |
| 1.00              | 0.403                 |
| 1.25              | 0.646                 |
| 1.50              | 0.947                 |
| 1.75              | 1.295                 |
| 1.79              | 1.355                 |

## Description of Control Scheme

Coordinated Control and the Control Hierarchy - The arm is controlled with a hierarchy of control algorithms, each level uses the next lower level to implement its functions. At the highest level, chains of commands, or macros, can be executed for such common functions as fetching or storing an instrument. This level does some rudimentary path planning to avoid bucket contact with the petals and other lander structure and produces a chain of straight-line motion segments, pauses, re calibration operations, and bucket-positioning commands. This level of control is one of the two primary levels through which commands from Earth will be executed.

The next lower level, also directly commandable from earth, executes the primitive motion commands from the top level. These commands, chained together in a linked list data structure, are executed in sequence until the end of the list is reached, after which the current position is maintained until a new list is received, either directly from uplink or from the top control level. The principal command executed at this level is a "move to" command, in which the arm is to move the bucket in a straight line from its current position to a new position at a specified rate.

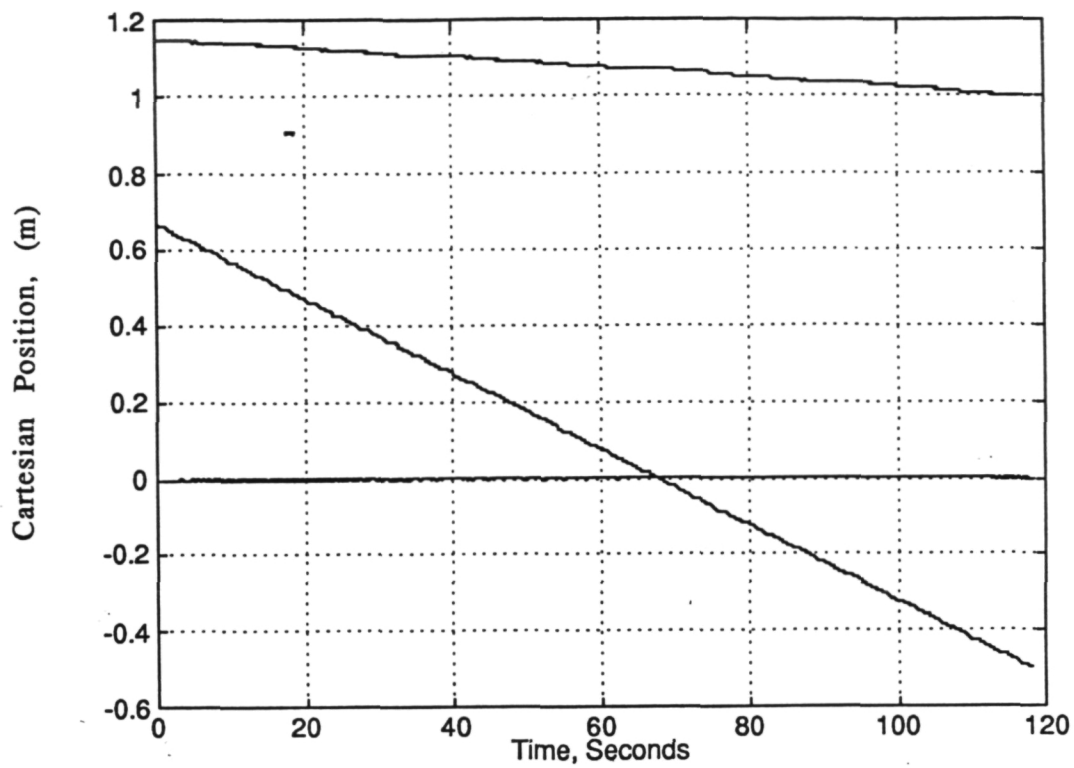
To execute a "move to" command, the control computer first measures the current joint angles, then determines what the joint angles will be at the end of the line segment by using inverse-kinematic calculations. The change in joint angle is then calculated for each joint, and the time allocated for the line segment is calculated by dividing the length of the segment by the commanded velocity.

If all joints are to rotate less than 100 mrad (approximately  $6^\circ$ ), each is simply stepped at a constant rate, generally different for each joint, that will result in reaching the new arm "pose" at the end of the allocated time.

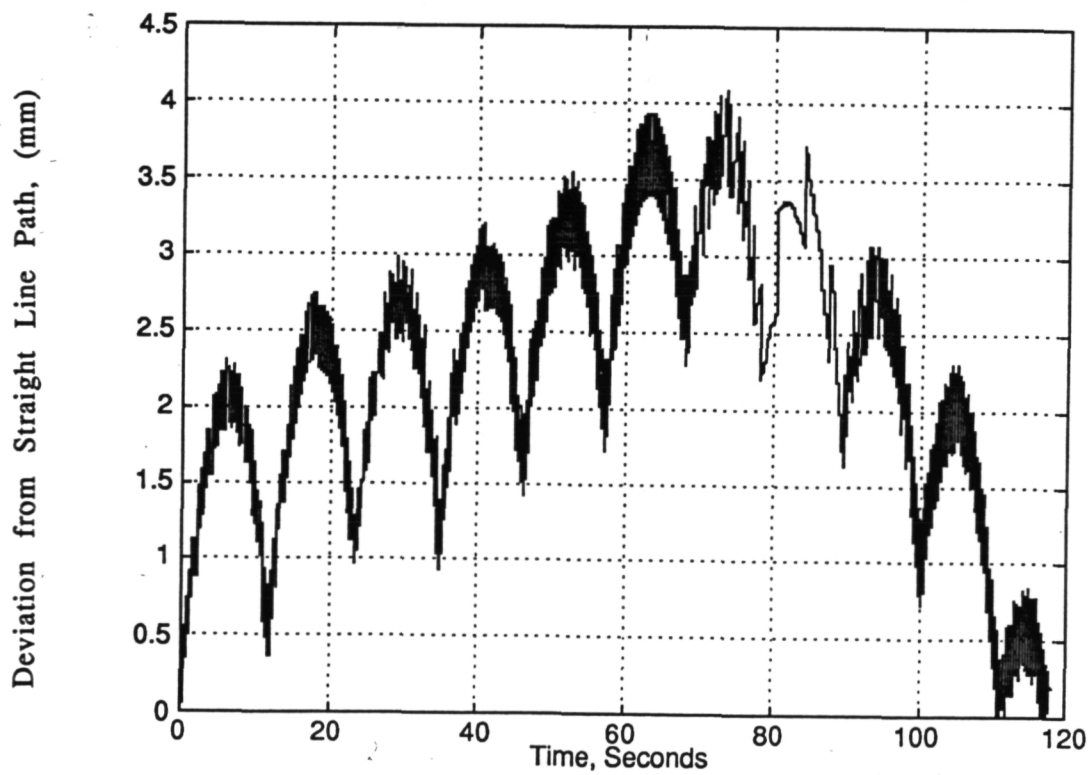
There is, however, a maximum allowed stepping rate. This maximum is imposed to minimize problems with missed steps, which result from a joint's having to react to torques caused by acceleration of other joints. For example, consider what happens if the arm is straight, parallel to the ground, and holding a camera and the shoulder pitch (elevation) joint moves the arm up. The elbow must apply a relatively large torque just to keep the arm straight. Reaction torques have been computed for representative arm motions, and the calculations suggest that stepping rates should be no higher than about 10-30 steps per second to allow the elbow to "catch up" to the shoulder between steps. This step rate corresponds with bucket velocities on the order of 1 cm/s when the arm is near the middle of its range of extension.

The step rate is therefore modified to limit the step rate of the fastest joint, and the rates of the other joints are decreased in proportion. The motion will then take the intended path, although at a slower pace than commanded.

When one or more of the joints must move more than 100 mrad, uniform-rate joint rotation would produce a bucket path deviating significantly from a straight line. This is undesirable, because it complicates path planning and collision avoidance. In this case, the control algorithm calculates what fraction 100 mrad is of the total rotation for the joint that must rotate farthest. It then sets up an intermediate goal a fraction of the total commanded distance from the starting point. This "chunk" of the commanded motion can then be handled in the same way as small moves. When the arm reaches the end of the "chunk," the control algorithm treats the remainder of the move as a new command, starting where it left off. The result is motion that closely approximates uniform-rate straight-line motion with a series of small arcs as shown in Figures 2 and 3. These figures consider only errors due to the algorithm and do not reflect other sources of error such as dynamic response and arm "sag" due to gravity and compliance of the arm.



**Figure 2 - Cartesian Coordinates of Bucket vs Time for Line Segment Requiring "Chunking"**



**Figure 3 Error from Straight-Line Path for Motion of Figure 2**

Upper-Arm Joint Control - Joints in the upper-arm, from the shoulder yaw joint through the elbow roll joint, are controlled by stepper motors, with position sensing via Resolvers (discussed in the next section). This section describes how these motors are controlled within a "chunk" of motion, as defined in the previous section.

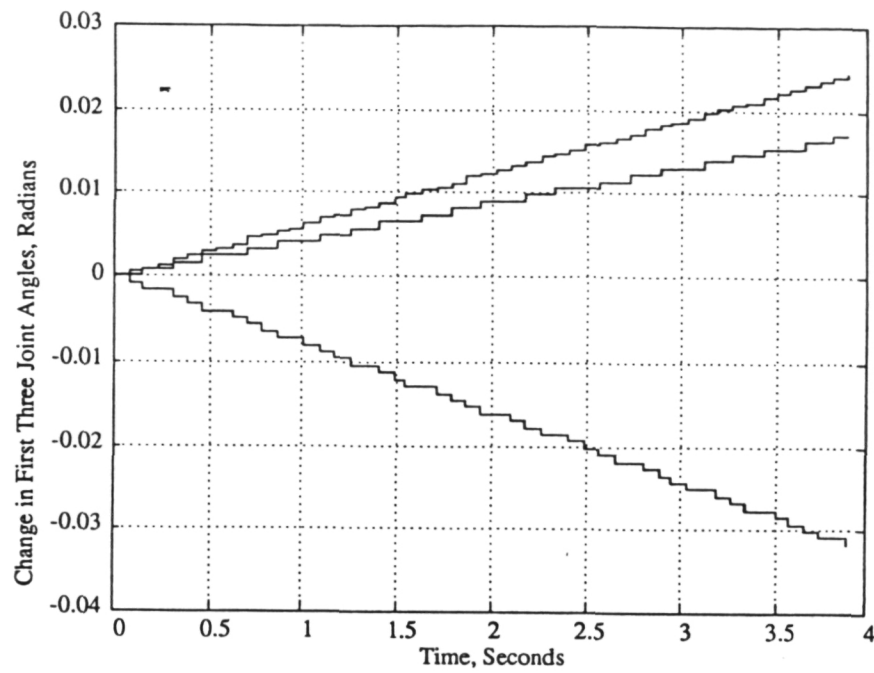
Commands from Earth directly to this level will be possible but are not expected to be used for common operations. The position sensors will not be used in a traditional feedback control scheme. Rather, for simplicity, stepper motor steps will be timed to provide the desired rates, and steps will be counted to stop at the specified angle. The position sensors will be used periodically as a "sanity check" on the step counts, because it is expected that steps will occasionally be missed and because the weight of the arm and loads will cause sag due to arm compliance. At least at the end of each motion segment, the true positions of the joints will be sensed after arm settling. Steps will then be added to move to the intended position and realign the step count with the position sensor readings. Control is therefore fundamentally open-loop with periodic recalibration. Where positioning is critical, small motion commands will ensure frequent recalibration. Zero-length motion commands can be used to force the recalibration without changing from the last commanded position.

A function in the software coordinates the steppers to move the arm in a straight line at a uniform rate without servicing interrupts at a different rate for each motor. Furthermore, although the computing burden would be reduced somewhat and the code simplified by use of a programmable interrupt timer, interrupts can be set up to occur at a fixed interval, independent of the motion being executed, provided that this interval is short compared to the fastest stepping interval. If a fixed interrupt interval is used, the interrupt service routine maintains a "wait count" to cause it to pass over a specified number of interrupts before acting on one. A one-millisecond interval worked well for this fixed interval in simulations, but rates ten times slower might be used.

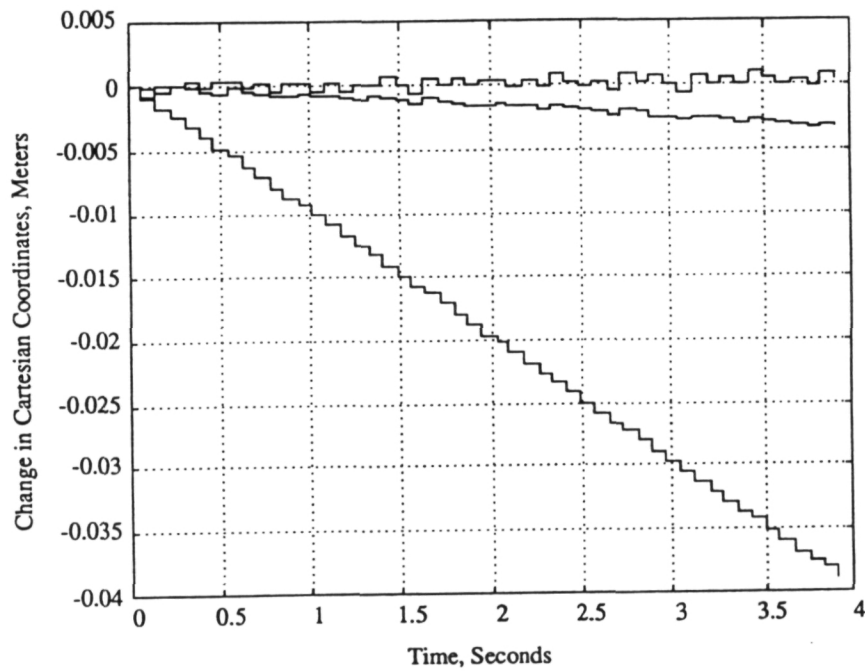
The interval at which interrupts are acted upon is calculated in the setup function before motion begins for a new "chunk." The interval is simply the time allocated for the chunk divided by the number of steps in the chunk for the motor that requires the most steps, rounded down to an integer multiple of the interrupt interval.

At each acted-on interrupt, the computer calculates the ideal number of steps each motor should have taken. If, for any motor, the actual number of steps differs from the ideal by more than half a step, that motor is stepped once in the direction that reduces the difference. The ideal count is simply the total number of steps in the chunk for the motor times the fraction of the allocated time that has elapsed. A variable in the software keeps track of elapsed time, in units of the interval between acted-on interrupts. The resulting joint motion versus time and Cartesian motion of the bucket versus time are shown in Figures 4 and 5, which are from a kinematic simulation model. The joint motion is monotonic and a close approximation to constant angular rate, although steps do not occur at regular intervals. Cartesian motion is not monotonic because a single step from one joint may contribute more motion to one Cartesian axis than multiple steps from a different joint. Nevertheless, deviations from a constant Cartesian rate are small over time intervals much larger than the stepping interval.



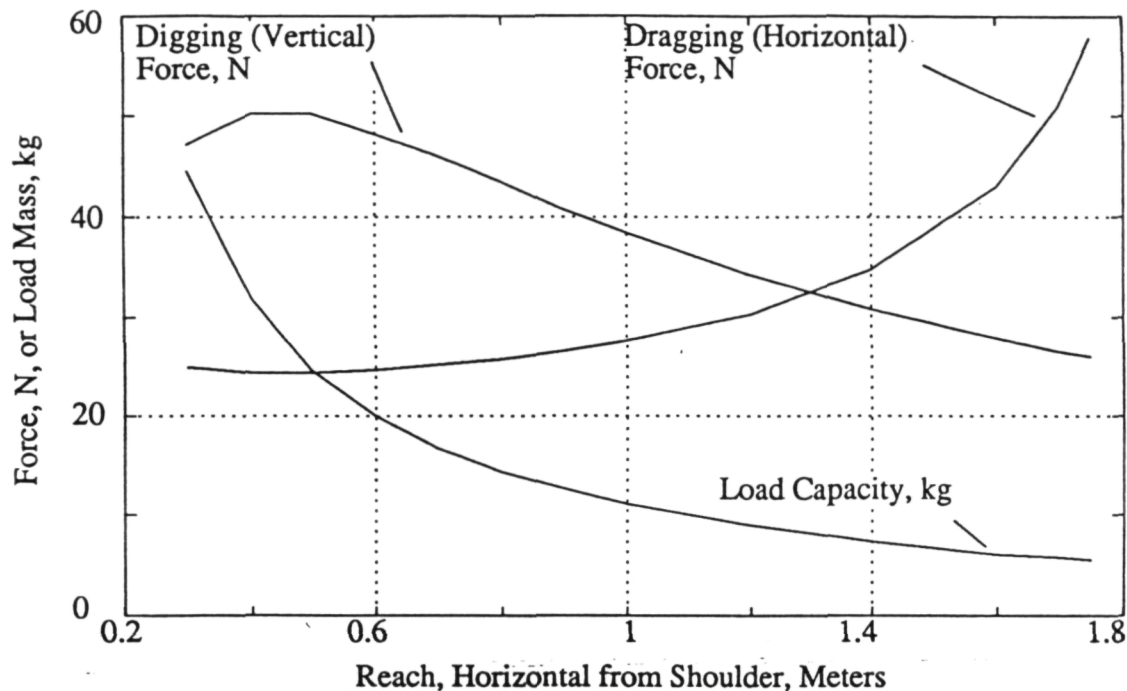


**Figure 4** *Change in Shoulder Joint Angles and Elbow Pitch Joint Angle for Motion of Figure 2, First 100 Steps*



**Figure 5** *Cartesian Motion Corresponding to Figure 4*

The dynamic simulation software was also used to generate the following graph (Fig. 6) which defines the predicted force and load capabilities for the SAID manipulator. Keeping in mind that soil sampling will occur at distances greater than 0.5 m, the graph indicates that the estimated forces produced by the arm are well matched for the task of digging and manipulating science instruments.



**Figure 6 Load and Force Capacity.**

#### **Selection of Upper-Arm Joint-Angle Sensors**

Some of the anticipated tasks for the arm, e.g., fetching and storing the camera, require positioning the bucket with the upper-arm joints to an accuracy of about 5–10 mm (0.2–0.4 in). Achieving this accuracy will require sensing joint angles accurately. The relationship between joint errors and position errors is defined by a Jacobian matrix, which varies with all the joint angles. Fully extending the arm, for example, makes vertical positioning errors most sensitive to shoulder joint angles but makes errors in position along the line of the arm very insensitive to errors in the shoulder joint angles. The pose in which the camera is fetched and stored, however, does not produce the greatest position error for a given joint error. An analysis based on representative poses and reasonable assumptions about additional error sources suggests an accuracy requirement of approximately  $0.1^\circ$  at the shoulder joints.

Any of a number of sensor types could be used to read the joint angles with the required accuracy, so a trade study was conducted to select the most appropriate device. Table 5 summarizes the results. Some other sensors, like Inductosyns, were not selected for the trade study because either they added complexity for accuracy that was not needed or their suitability for the application was questionable due to their size or other reasons. Inductosyns, for example, can provide accuracy to 0.5 arc seconds, over 700 times better than the requirement. Some others, such as capacitive and inductive sensors and sensors based on eddy currents were rejected at the start of the study because of angle range constraints or concerns about linearity and the complexity of support electronics.

**Table 5 - Joint Angle Sensor Selection Tradeoff Table**

| Criterion                                       | Weight | Resolver | Absolute Optical Encoder | Incremental Optical Encoder | RVDT | LVDT | Potentiometer |
|-------------------------------------------------|--------|----------|--------------------------|-----------------------------|------|------|---------------|
| Cost, Including Computer Interface              | 10     | 8        | 10                       | 10                          | 4    | 4    | 9             |
| Weight and Size, Including Computer Interface   | 9      | 9        | 10                       | 10                          | 6    | 6    | 9             |
| Life and Environment Compatibility              | 8      | 10       | 6                        | 6                           | 10   | 10   | 8             |
| Ease of Reading Absolute Angle                  | 7      | 10       | 10                       | 3                           | 10   | 8    | 10            |
| Power Consumption, Including Computer Interface | 6      | 8        | 8                        | 10                          | 6    | 6    | 8             |
| Weighted Total Score                            |        | 359      | 356                      | 319                         | 280  | 266  | 353           |

As with the actuators, overall cost was the chief concern. For some of the sensors, the cost of the sensor itself is misleading. Whereas the optical encoders can interface to a computer almost directly, Resolvers, LVDTs and RVDTs require an ac excitation supply and digitizing circuitry to interface to the computer. Even a potentiometer requires a dc supply voltage for excitation and an A/D converter. (To achieve 0.1° accuracy with a potentiometer, the voltage across the device must be used as the reference voltage for the A/D converter, which somewhat complicates the circuitry, and even then, this accuracy may be difficult to achieve). Similarly, the LVDT and RVDT have outputs proportional excitation amplitude, so excitation amplitude would have to be measured unless 500 ppm stability of the excitation could be assured. Even the suitability of these devices for the application is difficult to assess, inasmuch as they are not primarily designed as absolute-position sensors. For Resolvers and potentiometers, R/D and A/D converter modules are readily available components, so design time would be minimal for the interface. Differential transformer interfaces could be made with RMS-to-dc converters followed by A/D conversion, but achieving the required 0.05% accuracy with this approach would be difficult at best. Transicoil Inc. makes dc-to-dc LVDTs, which avoid the conversion circuitry, but their linearity is only 0.25%, which translates to errors over twice the budgeted limit.

Weight and size parallel the cost, because the interface circuitry strongly influence both. The high score given to optical encoders assumes that devices with built-in interface circuitry can be used. For this application, this may or may not be practical. However, even if only a read-station is provided in the encoder, the added circuitry for computer interfacing is straight-forward and small.

Life and compatibility with the environment favor devices with no internal electronics, since it is desirable to minimize power use for heating in the arm. In addition, the non-optical devices are more rugged, and the potentiometer and optical devices are more affected by the potential for dust contamination than the other sensors.

The whole reason for providing the angle sensors is to read absolute angles as a sanity check and calibration for the step-counting control scheme. As a result, incremental encoders were ranked low, since they count from a reference scribe rather than providing a direct readout of absolute angle. If the count becomes suspect, the joint must be moved past the reference scribe for recalibration, and if that is to be done, the motor counts can just as easily be recalibrated; much of the value of the sensor is lost. The LVDT has a reduced rating because its output is a nonlinear function of joint angle. Some processing would be required in the computer to convert its reading.

Finally, power consumption was considered. Again, the interface circuitry is a large factor. The incremental encoder is hard to beat, since its only significant power use is in the light source. The differential transformers were rated lowest due to the power required by their excitation and digitizing circuitry.

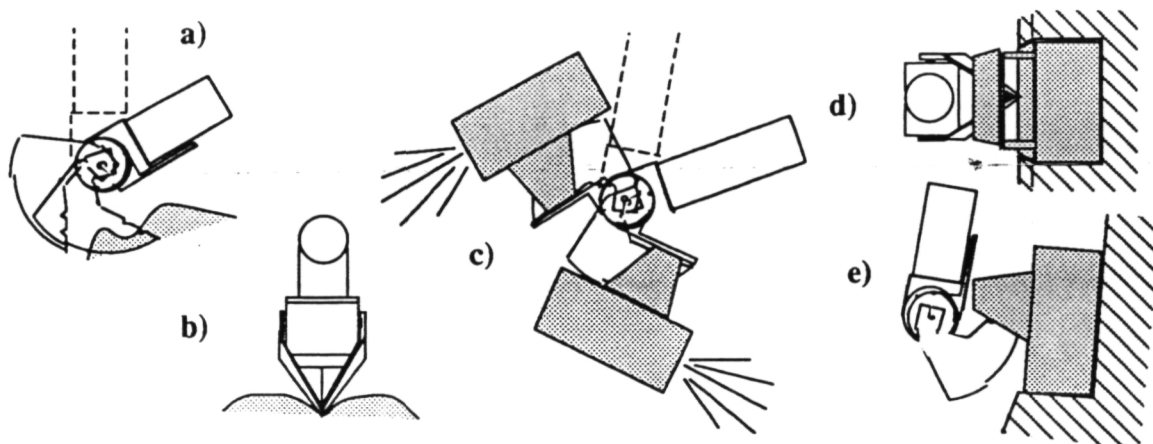
The results show that Resolvers have a slight advantage over absolute encoders and potentiometers, but that all three are reasonable candidates for the application. However, the technical risk in use of potentiometers is higher, inasmuch as the required accuracy will be difficult to achieve. Absolute optical encoders also may be risky in that their internal electronic parts may prove inadequate for the cold environment. If it is found that this makes internal parallel-to-serial conversion impractical, an absolute encoder would require routing approximately 15 wires per joint back to the computer through the arm, which is highly undesirable.

It should be noted, however, that  $0.1^\circ$  accuracy is at the edge of what is achievable with a single-cycle Resolver. Typically, a single-speed Resolver has accuracy of about 3–7 arc minutes (0.05 to 0.1 degree), and errors in the R/D conversion can degrade that accuracy further. R/D converters are available with 16-bit output (e.g., Analog Devices' AD2S80A), but for the average Resolver, the least significant two or three bits are essentially random. Any tightening of positioning requirements will require reassessment of the suitability of these sensors. At this point, Inductosyns become attractive despite their size ( $1\frac{1}{2}$ –2-inches diameter for an unboxed unit that mounts on the joint axis directly). In principle of operation there is little difference between a Resolver and an Inductosyn, but the latter is capable of very high accuracy and resolution. However, an Inductosyn sensor would also require routing approximately 19 wires per joint back to the computer through the arm, which is highly undesirable. These considerations led to selection of Resolvers for the upper-arm joint angle sensors.

## Wrist Development

### **Soil Acquisition**

Most of the soils expected to be encountered on Mars are relatively weak in strength as far as soils go. However, on Mars there is an excellent chance of encountering much stronger materials also, for example, water lane deposits, permafrost soils or polar ice deposits can be expected to have considerable strength. It is also, desirable to have the ability to measure the strength of the soil while sampling with the acquisition device. The soil bucket design that seem to provide the best chance of satisfying these desires is a simple backhoe with tapered sides so that the bottom of the bucket comes to a point (see Fig. 7a-7b). This way the leading tip of the bucket would be very pointed for scratching at or plowing through high strength materials. Also, the bucket capacity increases rapidly when being pulled through weaker materials at a greater depth, which would allow trenching operations in weaker materials to be feasible. The maximum capacity is 125 ml. The buckets profile is pushed forward so that the leading edge provides clearance for the trailing portions of the bucket. The shape memory muscles are monitored with load cells to prevent over straining. These load cells can also be used to monitor the cutting resistance of the material being sampled. Alternative designs such as a clamshell or three pedal sampler require more than one blade surface to be pulled through the material, which makes strength measurements more complex and requires more force from the actuator.



**Figure 7** Soil acquisition and instrument deployment concept: a) Bucket shown in acquisition and dumping positions. b) Front view showing pointed tip for acquisition in high strength materials. c) Range of angles which instruments can be deployed. d) Top view of grasping or stowing an instrument. e) Side view of grasping or stowing an instrument.

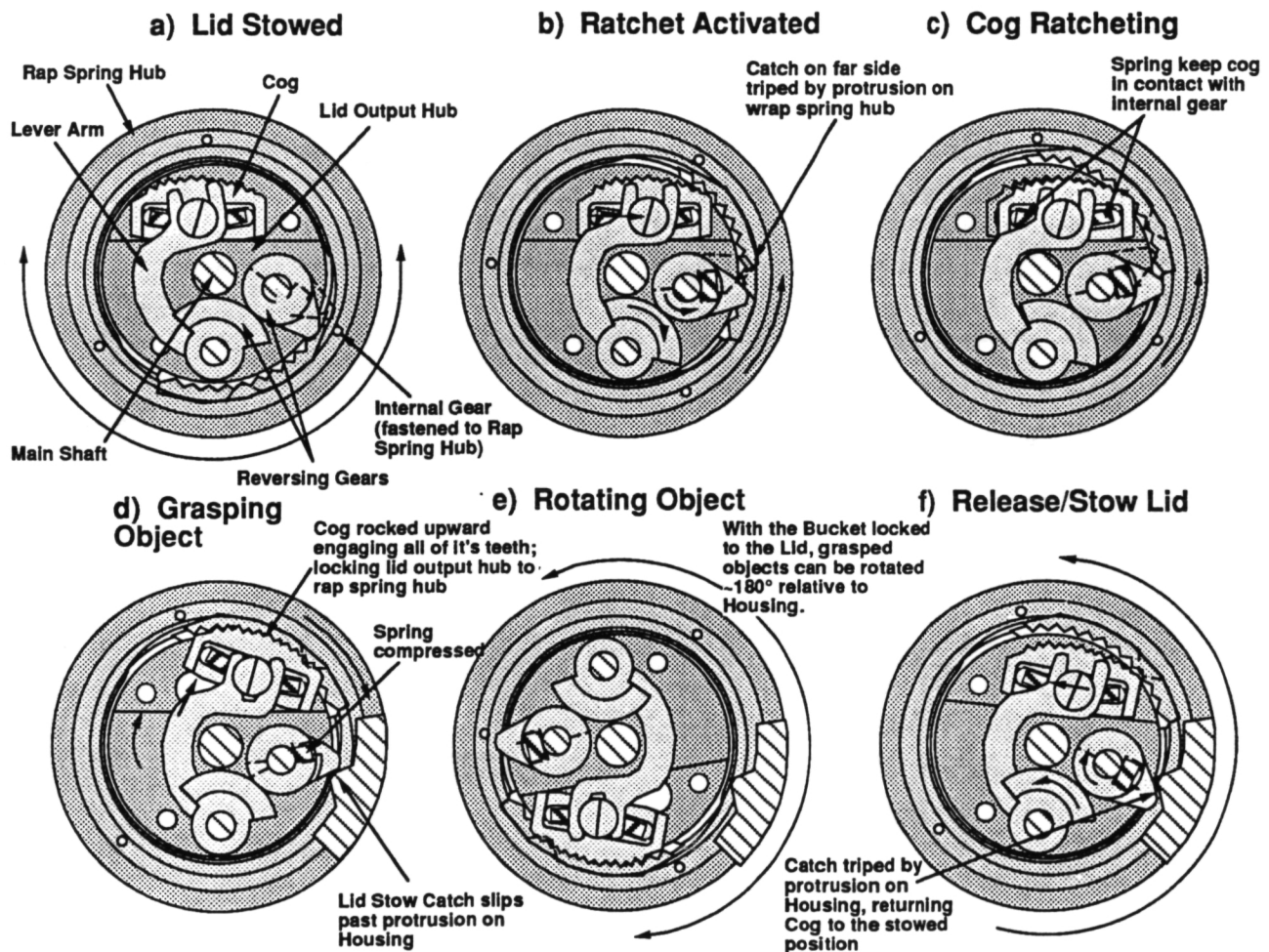
### **Grasping System**

**Concept** - The pointed bucket shape is appropriate for capturing objects of different shapes much the same as a hook. Also, the pointed tip allows for misalignments when attempting to capture the inverted U-shaped handle envisioned for instrument deployment (Fig 7d-7e). By having a lid on the wrist assembly which can act as an opposing thumb, objects can be held. If the lid can hold itself tightly to the bucket the wrist actuator can be used for grasping, as well as a degree of freedom which can rotate the end effector. A mechanism was devised which could lock the lid to the bucket when the bucket reached a position  $45^\circ$  from fully closed. At this point the mechanism would allow the bucket to continue to close



on the lid while the mechanism's ratcheting action would prevent the bucket and lid from separating. This way objects 4 cm or less can be captured and grasped between lid and bucket when the bucket is near the fully closed position. Once grasped the wrist actuator can rotate to any position(see Fig 7c). When the bucket is returned to within 45° of fully closed the mechanism releases the lid for stowage. 45° from fully closed was chosen for a grasp and release point because it is ideal for deploying instruments and these positions are not particularly useful for soil acquisition.

**Mechanical Design** - The design of a passively activated locking/releasing mechanism was appealing for one main reasons, it does not require an additional actuator when the wrist actuator can easily provide the needed actuation force. This saves mass at the end of the arm, wiring through 3 of the 4 joints, and power for an additional actuator. However, it does confine grasping and releasing operations to within 45° of fully closed.



**Figure 8 Lid Lock/Release Mechanism Sequence**

Design of the mechanism centers around a small cog with teeth which when moved into position engages the teeth of an internal gear. The cog is spring loaded which allows the internal gear to ratchet past in one direction. When the internal gear is moved in the other direction the cog's end most tooth catches rocking the cog upward until all of the teeth are engaged preventing the internal gear from rotating without also rotating the cog and associated hub. The internal gear is mounted inside the wrap spring hub and therefore mechanically connected to the bucket output. The hub which the ratcheting cog resides on is also located inside the wrap spring hub where it can revolve freely around the main shaft. The ratcheting cog's hub is mechanically connected to the lid assembly. The sequence is illustrated in Fig. 8.

The mechanism is actuated by two small catches on the ratcheting cog's hub which are mounted to a common shaft. The catches protrude beyond the diameter of the ratcheting cog's hub. When the bucket is rotated in the closing direction to the 45° position a protrusion on the rotating portion of the wrap spring hub engages one of the catches which turns two small gears reversing the mechanical motion and moving the cog into ratcheting position. Upon returning to the 45° position for releasing the other catch engages a protrusion on the stationary portion of the wrap spring hub which returns the cog to the stowed position, thereby releasing the grasped object. The catches are spring loaded so they can move past the protrusions in one direction of rotation while catching in the other. The ratcheting cog's hub is machined from Torlon which has a very low coefficient of friction 0.06. Torlon is used as a bearing surface for the shafts, and it also allows the cog to slide freely. Torlon also has a coefficient of thermal expansion (CTE) which is within 1.1  $\mu\text{m/mK}$  of stainless steel. Therefore the shafts, cog, reversing gear, and internal gear have been machined from stainless steel, so that the mechanism can function over a wide range of temperatures.

#### **Wrist Mechanical Assembly (see Color Figure A9)**

The completed housing assembly is sealed from dust by Teflon spring-energized seals between the housing and lid outputs (1.5" ID rotary seal) and between the lid output and the bucket output (.25" ID outside face seal). These seals have skived edges for maximum protection from dust with a minimum of sealing force (1 lb. per linear in.). The housing sides also have glands for a Teflon seal that mates with the housing cover to prevent dust from contaminating the wrap springs and associated mechanism. The bearings for lid and bucket outputs are nested inside the housing sides, and are sealed from dust. For redundancy the bearings are also of the sealed variety with no lubricant, and are commonly available as Mil Spec bearings.

The precision potentiometer used was manufactured as a custom part by McCulley Inst. Corp. for the SAID contract. It is similar to those manufactured by McCulley for space qualified gyro assemblies and is unhoused with a total mass of only 1.6 g. There are two wipers which make contact, one on each side of the resistive element of the potentiometer. In the SAID application one wiper would be used for the bucket's position and the other for the lid's position sensing. The resistive element is mounted to the housing with alignment screws.

The wrist assemble has been machined from aluminum (housing elements, lid and bucket assemblies), stainless steel (shafts, bearings, lid lock/release gears and cog), and Torlon 5030 (muscle pulley, lid lock/release hub, lid output bushing). Torlon after machining was recurred as specified by the manufacturer for 21 days ramping up to 500°F. It should be noted that assembling and disassembling the unit has not been as easy as we had hoped, and requires some skill of the technician. Alignment of the potentiometer elements is perhaps the most difficult, however we have been able to assemble and disassemble the unit many times without damaging or having to replace any of it's components. Table 6 summarizes the major components of the lower arm and their mass.

**TABLE 6 Actual Mass of SAID Forearm, Wrist and End Effector**

| <b>Wrist, End Effector &amp; Forearm Assemblies</b> | <b>Assembly Mass (g)</b> |
|-----------------------------------------------------|--------------------------|
| Lid Lock/Release                                    | 31.07                    |
| Rap Spring Brake                                    | 90.54                    |
| Pulley, Main Shaft & Coupler                        | 68.23                    |
| Bearing                                             | 50.21                    |
| Seal                                                | 8.40                     |
| Position Sensor                                     | 1.60                     |
| Muscle                                              | 124.70                   |
| MLI Blanket                                         | 120.40                   |
| Housing                                             | 111.67                   |
| Bucket End Effector                                 | 94.50                    |
| Lid for Bucket                                      | 83.49                    |
| Forearm Composite Tube                              | 200.00*                  |
| <b>Total</b>                                        | <b>984.81</b>            |

\*Estimated mass

## **Wrist Testing**

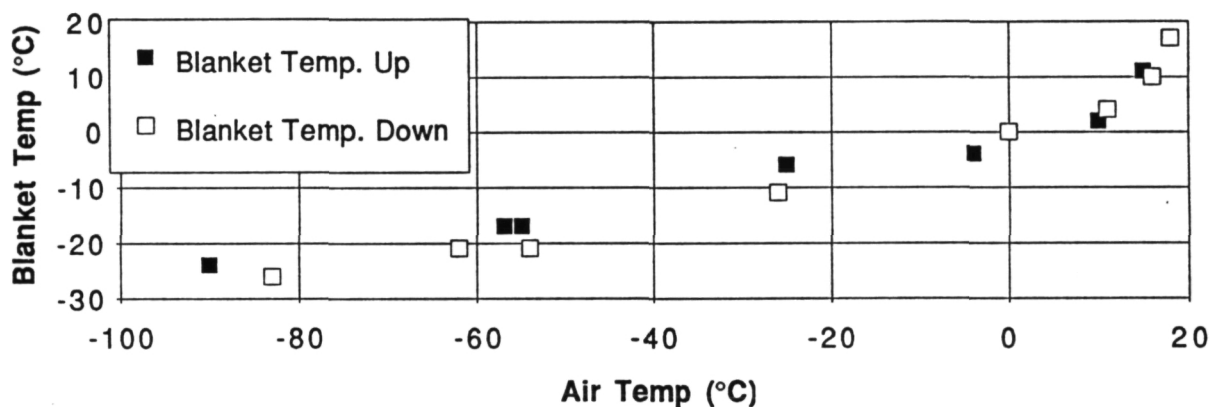
The End Effector, Wrist, and shape memory muscle actuator assemblies fabricated for the SAID program have been tested for operational power, torque output, and soil sampling capabilities. For testing, these assemblies were mounted into a fixture which could hold the assemblies in the proper positions for testing and also function as the forearm structural member, which has not yet been fabricated (see Color Figure A1). LabView Software was used to control the wrist and acquire data. The software monitors lid and bucket position, load on the muscles, voltage and current draw by the muscles, and load from an external load cell used to measure tip force. It controls the Wrist end effector with a simple algorithm which allows setting of the desired position, an initial current level for warming up the muscle, a Ø2 allowing a separate current setting for movement, and Ø3 allowing a third current setting for slowing the motion just before the desired position is achieved. We have had good success stopping the Wrist to within  $\pm 2^\circ$ . A more sophisticated version of the algorithm has been developed but not yet implemented. It should allow greater position control, and hopefully allow us to achieve or goal of  $\pm 1^\circ$  accuracy or better.

## Power Testing

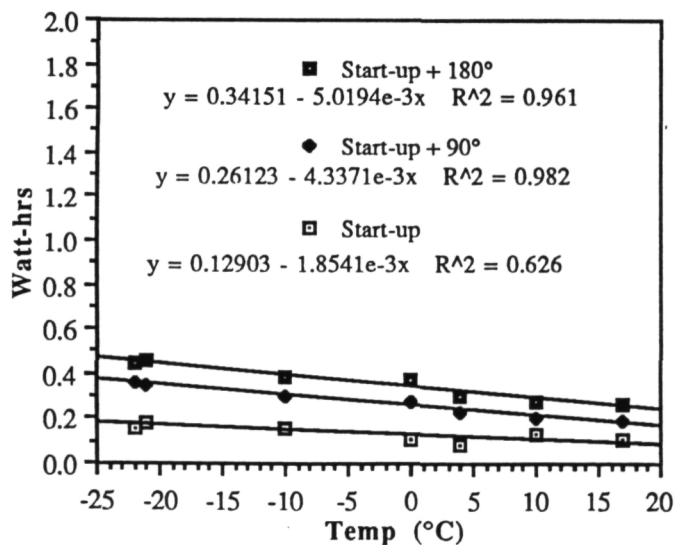
The shape memory muscles power utilization is dependent upon the temperature and pressure of the environment in which it is operating. For these reasons the system needed to be tested in a vacuum chamber at cold Martian temperatures, and low pressures. The move toward a vacuum environment lowers the power required by the muscles, however the colder temperatures have the opposite effect. The muscle built by Martin Marietta before this contract used 24 wires and required 1.4 watt-hrs for 90° of motion in the up (open) direction at nominal Martian temperature and pressure. We had hoped that the 8 wire muscle built for SAID would greatly reduce the total energy as well as the required current. Unfortunately, the current required for efficiently warming the SAID muscles below -60°C is 2.35 amps, virtually the same as the 24 wire muscle. The energy required for motion was reduced by 40-60%.

The muscles are wrapped in Multi-Layer Insulation (MLI) blankets, which improve the power characteristics by 65% or more depending on temperature and pressure conditions. Since it is not possible to monitor the temperature of the shape memory wires without shorting them, the temperature of the blankets was monitored along with the air temperature inside the chamber. During operation, after the initial muscle warm up blanket temperatures can be expected to stay well above the air temperatures for hours after the muscle has been turned off, as was the case with the SAID tests (Fig. 9). Figure 10a and 10b show the energy used for various blanket temperatures at Martian pressures. Start-up power is included in the 90° and 180° measurements.

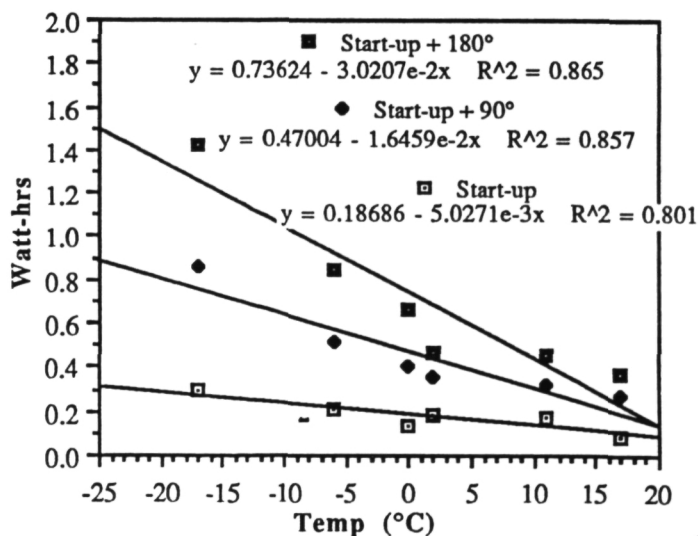
**Figure 9 Air Temperature vs. Blanket Temperature**



**Figure 10a Energy for Down Motion**



**Figure 10b Energy for Up Motion**

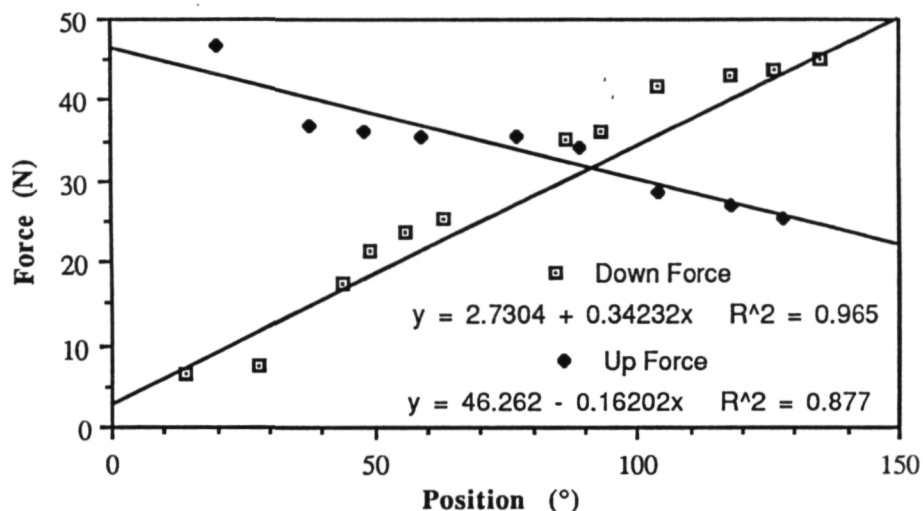


The mechanisms has worked smoothly in the thermal/vacuum chamber down to the coldest temperature tested, -90°C. We did experience drop-outs in position readings from the potentiometer at temperatures below -60°C, which we have attributed to an undiagnosed CTE problem. Except for these drop-outs the sensor has been 100% reliable through 100's of cycles at temperatures above -60°C.

### Torque

The torque which the muscle can supply is a function of position. This is because the activated muscle is reloading the other muscle when moving. The lowest torques are when the bucket position is near fully closed or fully open (see Fig 11). This works out well since these positions are not generally used for digging, lifting or other functions requiring high torque.

**Figure 11. Wrist Force with Position**



### Soil Sampling

Soil sampling tests were performed to verify the mechanisms designed ability to acquire soil samples and explore the systems ability to make measurements of the soil properties during an acquisition. The load cells which monitor each of the muscles, to prevent over straining, can also be used to monitor loads from cutting resistance when the bucket is pulled through soils. The additional load from the soil work can be subtracted from the normal loads produced when one muscle reloads the other. If the loads on the bucket can be measure in this manner with enough resolution and accuracy, then perhaps determination of the physical properties of the soil being sampled could be estimated.

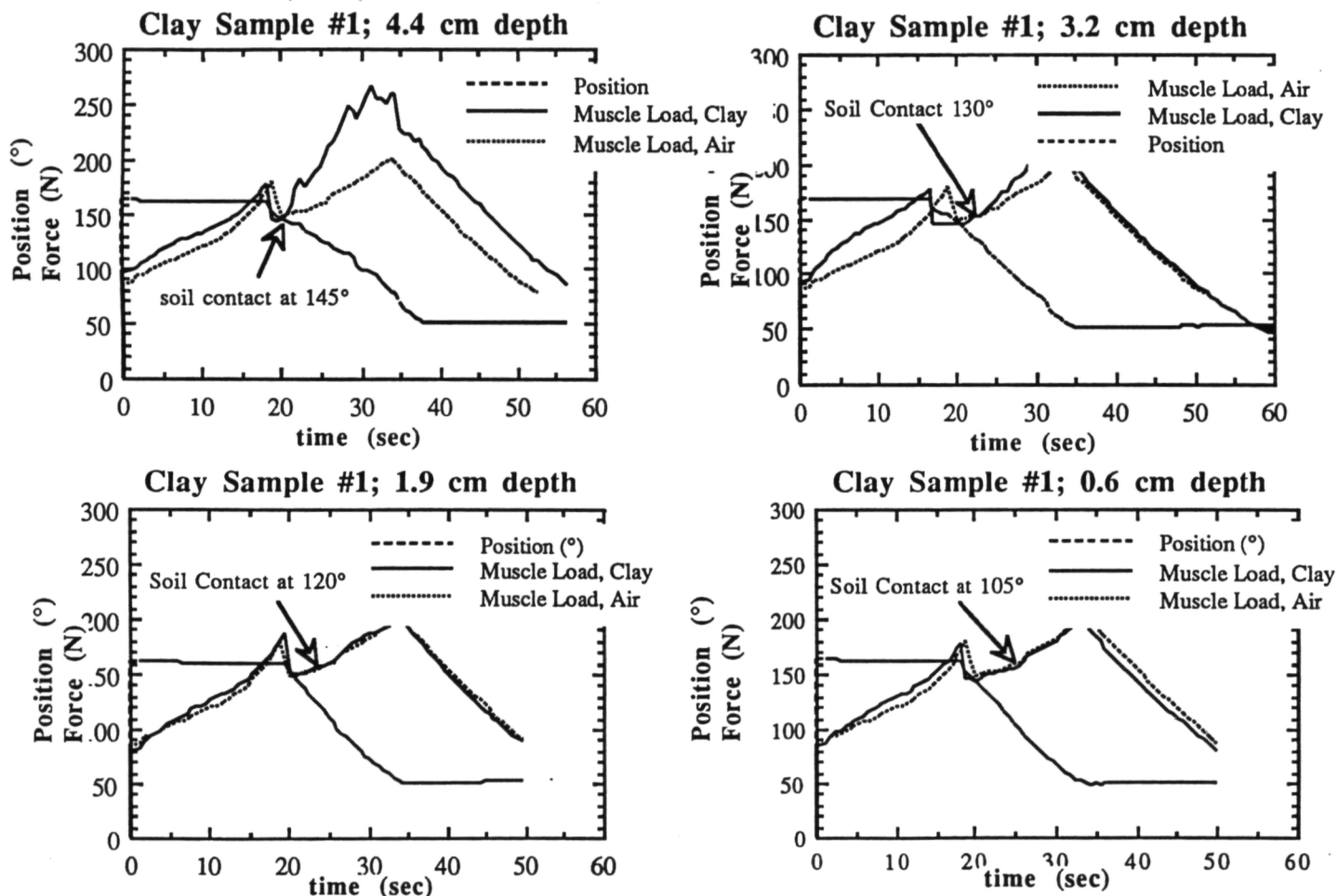
Soil samples were prepared by the PI, which were analogous to Martian soils. Because of the uncertainty of the Martian soils properties and mineralogy, a variety of samples were prepared. The samples were tested by the USGS Soil Testing Lab in Golden Colorado so they could be accurately reference and compared to other soils. The testing involved the direct shear method which defines both the cohesion and the angle of internal friction of a sample. Mineralogy and densities of the soil was also recorded along with the method used to compact the soil. A summary of the soil types used for testing SAID can be found in Table 7.



**Table 7 Soil samples tested by the USGS, and used for SAID soil testing.**

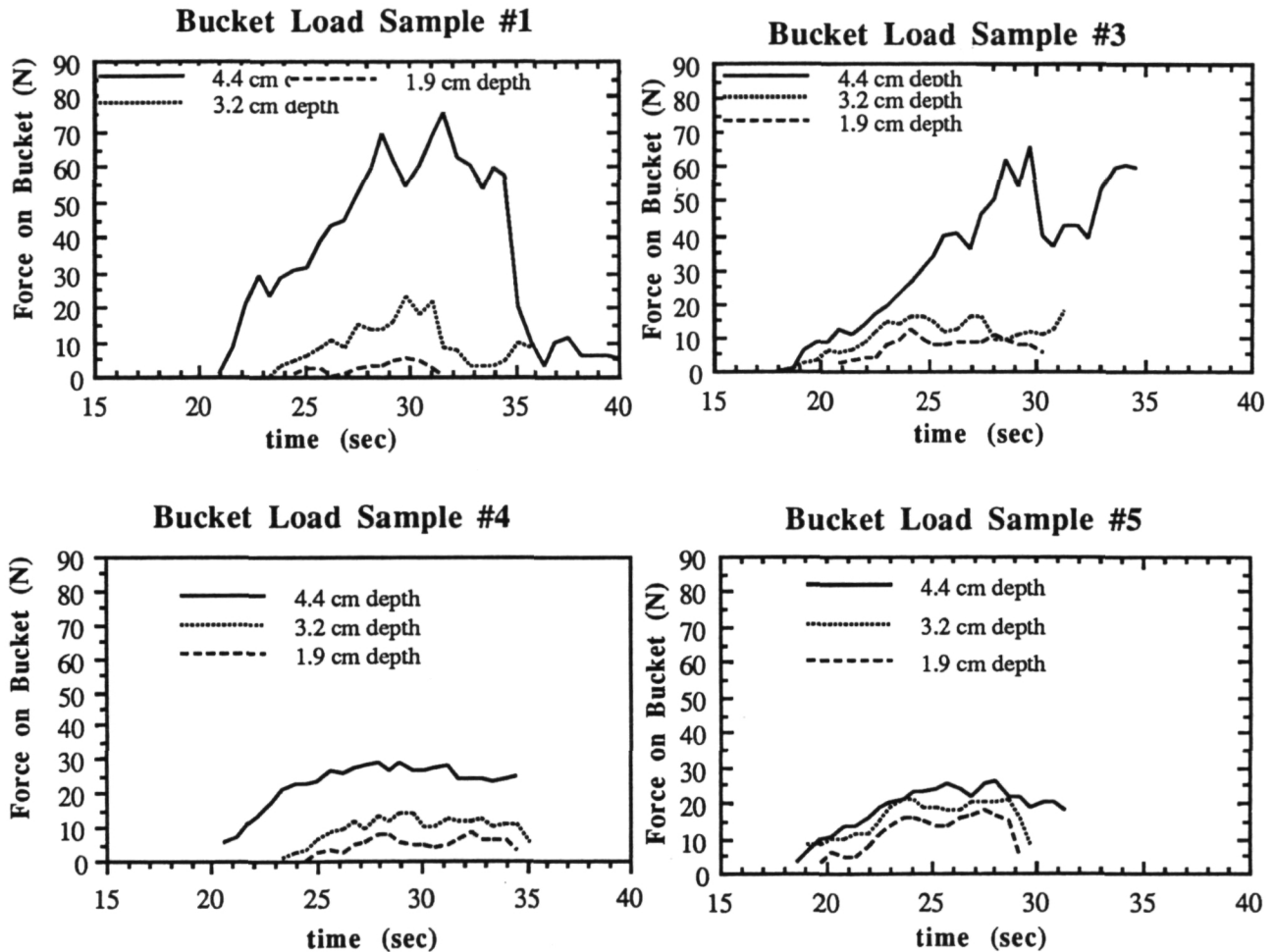
| Soil Sample | Composition                 | Grain Size                | Density | Cohesion | Angle of Friction | Shear Vane |
|-------------|-----------------------------|---------------------------|---------|----------|-------------------|------------|
| #1          | Clay-Nontronite, Compressed | 1-100 $\mu\text{m}$       | 1.41    | 43.1     | 31.8              | 7.0-7.6    |
| #3          | Cinders-Volcanic Dust       | 10-150 $\mu\text{m}$      | 1.47    | 66.0     | 27.3              | 7.5-9.1    |
| #4          | Clay-Nontronite             | 1-100 $\mu\text{m}$       | 1.25    | 7.7      | 38.5              | 2.5-3.0    |
| #5          | Sand-Quartz & Feldspars     | 250 $\mu\text{m}$ to 2 mm | 1.44    | 7.0      | 31.3              | 0.8-1.5    |

The bucket was pulled through each of the soil types at 4 different depths, although only the deepest 3 samplings produced useful data. While acquiring the samples, position and muscle load were recorded with time. This data is plotted with data from pulling the muscle through air (see Fig 12). The time at which the bucket first makes contact with the soil is recorded as well. The load associated with the soil resistance is plotted for different depths for all of the samples tested (see Fig 13). Clearly the SAID system was able to distinguish the weaker soils (sample #4 and #5) from the stronger one (sample #1 and #3).



**Figure 12 Sample Acquisition in Clay, Sample #1 at Various Depths Compared with No Load Acquisition through Air.**

We are encouraged to see that the system can record meaningful data even in very weak soils such as sand. Also encouraging was the comparison between sample #1 and sample #3, which have similar cohesion's and different angle's of internal friction. The steeper angle of the load building up on sample #1 may be reflecting the higher angle of internal friction measured by the USGS. After reducing this data it was observed that the signature of the curve building up force until the soil suddenly fails from shearing may correspond more closely to the signatures produce during the direct shear testing failures. This may be a more useful method of determining the soil's properties than comparing the reduced results of the direct shear test which report cohesion and angle of internal friction.



**Figure 13** Load on Bucket from Sampling Operations at Various Depths for the 4 Soil Types Described in Table 7.

Although we have not taken enough data or performed enough analysis of the cutting properties of this bucket design to devise an accurate method of determining soil properties from the sampling, we have shown that these measurements are feasible with the SAID system. Quantitative correlation's will require much more soil testing, so that repeatable results are confirmed, and theoretical analysis are developed so that greater understanding of how the bucket interfaces with the materials being sampled can be achieved. The magnitude of this effort is out of scope with the present contract funding level.

## **Upper Arm Joint Development**

### **Gear Reduction System Development**

The gear reduction system for the shoulder pitch, shoulder azimuth, and elbow pitch joints utilized harmonic drive component sets and spur gears. The spur gears are arranged on the input shaft of the harmonic drive to reduce the start-up torque required for the motor, and where their backlash will contribute very little to the overall backlash of the system. The shoulder and elbow pitch joints constructed for testing used 96 pitch 22 tooth pinions on the step motors and a .125" wide, 96 pitch, 180 tooth spur gear (see Color Figure A3). Harmonic Drives were procured as component-sets which consist of three elements; 1) Circular Spline, 2) Flex Spline and 3) Wave Generator. The components were dry lubricated by sputtering Gold and Molybdenum Disulfide onto the teeth of the Circular Spline and Flex Spline and on the bearing races, balls, and Oldham coupling of the Wave Generator. Three sets were lubricated for upper arm joints; a Size 20, Size 17, and Size 14. Sizes were selected based on acceptable spring rates and manufacture recommended safe torque's when used in a 1 G environment.

### **Bearings and Housing Structure Development**

The mechanical load of the arm rest on a duplex pair of angular contact bearings. The size and number of balls were selected based on stiffness requirements and manufacturer recommended safe loads for dry lubricated bearings with relatively low cycle life requirements. Lubrication was sputtered MoSo<sub>2</sub> applied by the manufacturer. The ID of the bearings were selected to accommodate the OD of the Harmonic Drive needed for that particular joint. Thin Section Bearings were used because of their light weight. This required the Bearing Housing to provided structural integrity to the bearings. The design goal was to have less than 1 mm deflection at the arms tip attributed from the bearings, in 1G. To provide the needed axial support the bearing's ODs are held apart by parts 11510, 11610, 11710 for the Elbow Pitch, Shoulder Pitch and Shoulder Azimuth joints respectively (see Color Figures A7, A8 and A9). To provide the needed preload the ID's of the bearings are pinched between parts 11520 and 11530 for the Elbow, 11620 and 11630 for the Shoulder Pitch and 11730 and 11740 for the Shoulder Azimuth joint. Housing elements are machined from 416 Stainless Steel, because of it's near perfect thermal expansion match to the 440C Stainless Steel bearings. The cold temperature requirements also drove the design to use preload springs to load the angular contact bearings, because they provide a more consistent preload for the bearings over the extreme temperature range expected during operation. A set of radial bearings also with dry lubrication retains the input shaft which drives the Wave Generator.

### **Limb Structures Development**

Composite tubes were designed that would attribute a total calculated deflection of 10.2 mm at the tip when the arm is fully extended in 1 G, which translates to 5.35 mm in the 0.38 G environment of Mars. The finished Forearm tube is 99 cm (39") long, 5.7 cm (2.25") ID, with a wall thickness of 0.5 mm (.020"), and a mass of 166 g. The Upper arm tube is 86 cm (34") long, 6.9 cm (2.75") ID, with a wall thickness of 0.7 mm (.030"), and a mass of 258 g.

The composite tubes are mounted inside of thin metal sleeves. Inner sleeves made of Aluminum are tapped so that the composite tube is clamped between the inner and outer sleeves when screws are inserted. The outer sleeves are connected to the Shoulder and Elbow Pitch joint structures with parts 11540, and 11640 which bolt onto the Inner Bearing Housing parts, and 11560 which bolt onto the Elbow Outer Bearing Housing. 11660 bolts onto the Shoulder Outer Bearing Housing and then is fastened to the Shoulder Azimuth Outer Bearing Housing via parts 11700 and 11720. Parts 11540, 11640, 11560,

and 11660 were all made of 416 Stainless Steel to minimize deflections, and were the most difficult to machine because of their complex shape and thin wall thickness. However, their design enabled the designs of the other structural parts which are also made of 416 Stainless Steel, to be more simple to machine; because nearly all of the machine work can be accomplished on a lathe, avoiding expensive CNC machines.

### **Dust Seals**

The bearings, spur gears, motor and resolver shafts are sealed from dust contamination by the use of Teflon spring-energized seals. These seals maintain a constant force on the Teflon which alleviates cold flow concerns over long mission duration's. The seals have skived edges which are particularly well suited for dust sealing. They also have a minimum amount of spring force ( 1 LB per linear inch of seal) to minimize static friction. The Elbow and Shoulder Pitch joints are sealed with 4 seals each; 2 for sealing the bearings and 2 for sealing the harmonic drive, spur gear, resolver and step motor. Color Figure A4 shows the seal for the Resolver. These seals help provide some dampening to the uneven pulsing of the step motors. The Shoulder Azimuth joint needs only 1 dynamic seal, and 1 static seal with the Lander's deck.

### **Step Motors and Associated Electronics Development**

The step motors procured for the Elbow and Shoulder Pitch joints were both size 15 step motors to save on nonrecurring engineering. The motors are 45° steppers capable of supplying 16 in-oz of torque at 180 pulses per second, and 65 watts. The motors have 6 wires for unipolar or bipolar operation, and weight 187 g. The motor bearings are dry lubricated for low temperature operation. The motor housings and pinion shafts are made of 416 Stainless Steel. The motor mounting parts 11580 and 11680, spur gears and spur gear shafts are also made of 416 stainless steel, so that there is no change in the gear mesh through the extreme temperature range to be tested. Parts 11580 and 11680 also house the bearings for the spur gears and provide an additional mounting hole for a size 11 brake. Motor and Brake mounting holes are slotted in the vertical direction to allow gear mesh adjustments. A cover mounted between the motor mounts and 11585 for the Elbow Pitch joint and 11685 for the Shoulder Pitch joint, seals the spur gear compartment and provides access so that gear mesh can be observed and more easily adjusted.

Hybrid step motor driver ICs manufactured by MPC were used to pulse the step motors. These Hybrids are capable of driving the motors for bipolar operation to 2 amps or 50 watts. They can be qualified for space and would be an excellent choice for the flight electronics. Power was supplied to the hybrid by lab power supplies with current regulators which were set to prevent high current draws during cold temperature testing. The Hybrids are mounted on aluminum plates inside of a 386 computer. A digital I/O card procured for the 386 provided digital interface with the Motor Hybrid ICs.

### **Resolvers and Associated Electronics Development**

The Resolvers were manufactured by Transcoil with a requirement that they have  $\pm 3$  arc minutes accuracy. They are housed, Size 11 units which weigh 168 g, and mount to Aluminum flanges ( parts 11590 Elbow and 11690 Shoulder) which also seal the left side of the Elbow and Shoulder Pitch joints. A rectangular key, mounted to the Resolver's shaft, fits into the key way at the center of part 11520 in the Elbow and part 11620 in the Shoulder pitch joint (see Color Figures A4, A10 & A11), to measure angular motion on the output of the joint directly with a 1:1 ratio. The basic design of the Resolvers employs a cylindrical 2-phase, perpendicular rotor winding as the primary, inductively coupled to a symmetrical 2-phase, perpendicular stator winding. These units called "Resolver Transmitters" have 4 wires for sine/cosine data transmission and have better accuracy's than 3 wire Synchro type devices. A 1.2" bore, shaftless Size 25 Resolver manufactured by MPC is proposed for the Shoulder Azimuth joint. It is also a Resolver Transmitter type

which would measure angular motion of the joint directly and would have an accuracy of  $\pm 3$  arc minutes, and a mass of 112 g. The large bore of this unit allows the rotating structure enough diameter to keep deflections within design goals, while providing a direct measurement of angular displacement.

The Resolvers sine/cosine signals are converted to digital data by a Resolver-to-Digital Converter IC manufactured by Analog Devices, part 2S82A. The IC's are used in 14 bit mode providing better than 2 arc minutes resolution. The lab waveform oscillator was used to supply the required 400 Hz, and lab power supplies were used to supply the needed voltages. A small circuit was developed to drive the IC with an acceptable response rate, and accuracy. The IC's and their corresponding drive circuits are mounted inside the computer on vector boards, and connected to the 386's digital I/O board via ribbon cables.

### **Wiring Development**

The composite tubes house the cabling in the limbs of the arm. Cable pathways through the Elbow and Shoulder Pitch joints are similar. For example the cables from the forearm pass through parts 11550 and 11540 then wrap around the joint in the channel formed by part 11510, then pass through part 11560 and into the upper arm tube. The cables at Shoulder Azimuth joint pass through part 11700 and 11710 then wrap around part 11710 before leaving the sealed housing. Each Resolver required 3 twisted shielded pair wires for operation. Step motors require 4 #22 AWG wire for each, and the Shape Memory muscles require 2 #22 AWG wire for each. Connections were installed on either side of the Elbow joint to help facilitate assembly and testing.

### **Control Software Development**

The arm control software provides the capability to command the arm position by direct operator inputs or by a pre-recorded sequence of commands. Commands can be either joint angles or Cartesian positions for the soil scoop.

If a joint-angle command is given, the software rotates the joints at a steady rate so that both joints achieve their new commanded position simultaneously. Similarly, if a Cartesian command is given, the software coordinates the joint rotations to move the scoop in a straight line at constant Cartesian velocity to its new commanded position. In either case, the software produces a sequence of closely spaced joint position subcommands, one for each cycle of the 18.2-Hz interrupt clock. For joint-angle commands, the subcommands are generated by calculating the time needed to move the joint that must go the farthest and linearly interpolating between the end points. For Cartesian moves, the joint subcommands are derived from interpolation between the endpoints of the move, in Cartesian space, using inverse kinematics calculations.

The subcommands are used as reference inputs to a discrete-data servo loop for each joint. The loops execute at a 18.2-Hz sample rate and compute error as the difference between the subcommand reference and the measured joint position as indicated by the joint's resolver. The difference, multiplied by a loop gain, is the commanded joint rate. The rate is then converted to time between steps of the joint's stepper motor and rounded to the nearest multiple of the servo sample interval. This forces the joint to track closely the subcommands, even if dynamic loads cause missed steps.

For Cartesian moves, the inverse kinematics calculations are not done for each servo sample, due to their complexity. Rather, the straight-line path is divided into "chunks," each representing approximately one second of motion. The inverse kinematics calculations are done for points at each end of each chunk. Within a chunk, the joint subcommands change at a constant rate, but the small size of the chunks makes the overall motion a very close approximation to linear Cartesian motion.



The software is written in C++. Details specific to the interface—port addresses, the port bits used for control outputs and resolver reading inputs, etc.—are isolated in the TRobot class and its member functions. Two of the member functions of this class are used within the interrupt-service routine that implements the servo loop. These two functions are declared as inline to speed interrupt servicing.

The forward and inverse kinematics calculations are more general than needed for the present arm design; they allow for expansion to a 5-DOF arm when control of the bucket and shoulder yaw are incorporated into the design. The unimplemented joints are ignored for the current design, i.e., joint angles of zero are given to the forward kinematics calculations and joint-angle outputs from inverse kinematics are ignored for the unimplemented joints.

Certain parameters have not been optimized in the current version of the software. The constant 4000L in function TRobot::CalcCycles could be changed to increase robot speed. The calibration data in the kinematics header file (Listing 1) are not precisely measured. The resolver offsets in function TRobot::ReadResolvers do not account for the limbs (composite tubes and mounting hardware) deflection due to gravitational loading of the arm system. Optimization of these parameters, along with compensation for gravitational loading in subcommand generation, would improve the accuracy of arm positioning. Strain gauges have also been considered for the composite tube as a means of providing direct feedback to the software on limb deflections.

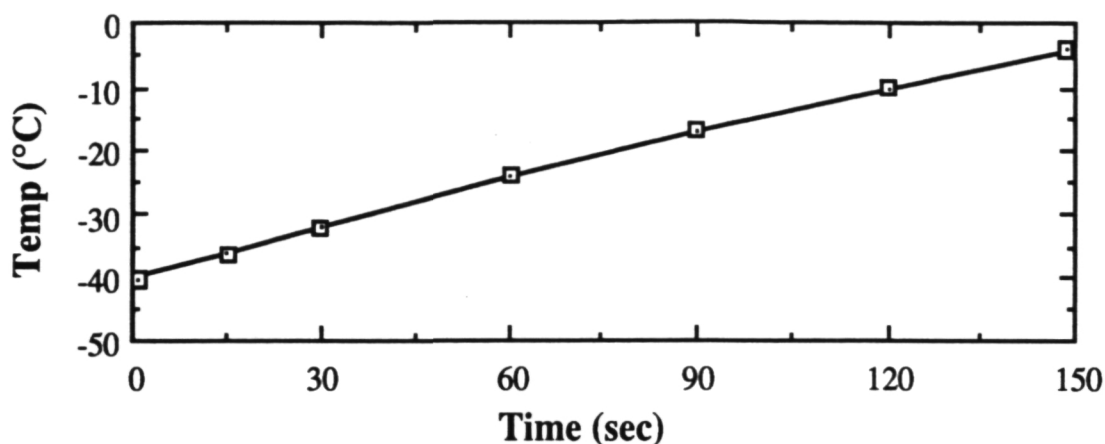
Other features that could be readily added include a pause command, which would be useful in playing back pre-recorded command sequences, and a relative-motion capability, so that commands could be given relative to the current position rather than in absolute coordinates. In addition, incorporating playback into the program as a command could be useful. Currently, playback is done by using MS-DOS I/O redirection to accept a file as the source of commands normally expected from the keyboard. These changes would represent relatively minor modifications to the software.

## **Elbow and Shoulder Pitch Joint Testing**

### **Environmental Testing**

The Bearing Assemblies of the Shoulder Pitch and Elbow Pitch joints were both tested at temperatures ranging from 21°C to -100°C, to assure that the preload on the angular contact bearings developed from the housings would remain constant. The bearings and housing assemblies worked well through the entire temperature range tested.

The Elbow Pitch joint was tested in a thermal vacuum chamber at Mars pressures, and temperatures from 0°C to -80°C. The joint was mounted to a short section of composite tube (see Color Figure A5). Another section of composite tube is attached in the same manner as the actual forearm tube. The end of this tube is packed with 2 kg of lead, which resulted in a torque on the joint of 3 ft-lbf when the forearm tube passes through the horizontal position. Then joint was controlled by the software and electronics described earlier. The chamber was pumped down to 6 mb pressure and maintained at that point. LN2 was used to cool the chamber's shroud. Tests were performed at 0°C, -20°C, -40°C, -60°C, and -80°C, with several cycles of 90° or more, in each direction, moving through the horizontal position, at each temperature. The step motors were current limited to 1.6 amps, using 38 watts for each test. The joint performed very well at all of the temperatures tested. Pulse rates as high as 15 PPS were used without skipping steps at each of the temperatures. A video camera recorded the cycles for later review. Figure 13 shows motor temperature rise data collected during the -40°C test.



**Figure 13. Motor Temperature Rise Measured at  $-40^{\circ}\text{C}$ , and 6 mb. Size 15 Step Motor War Operated Continuously at 38 watts.**

#### **Position and Coordination**

The wrist and forearm tube with shape memory muscles and associated mechanisms developed during the first year of contract effort were mounted to the completed elbow mechanism. The upper arm tube was mounted to the elbow joint and shoulder pitch joint. The shoulder pitch joint was mounted to an Aluminum plate which was attached to a manually operated rotating stage. The shoulder azimuth joint could not be constructed because of budget considerations. The completed joints and limbs of the system were weighed and their mass is summarized in Table 8.

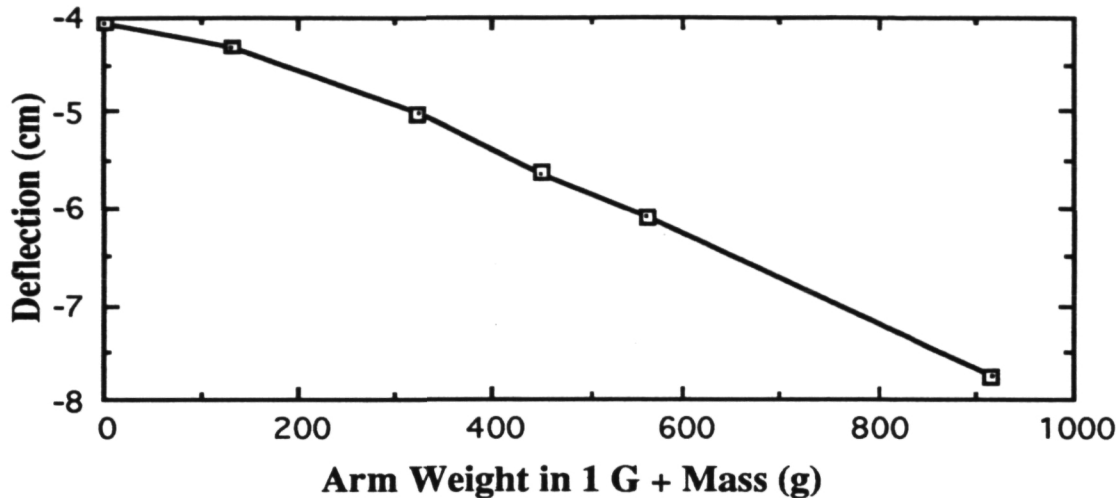
**Table 8. Actual Mass of Completed Arm Segments.**

| Arm Segment            | Mass (kg) |
|------------------------|-----------|
| Wrist & Forearm        | 1.202     |
| Elbow Pitch Joint      | 1.213     |
| Upper Arm              | 0.333     |
| Shoulder Pitch Joint   | 1.386     |
| Total for 3 DOF System | 4.134     |

The elbow pitch and shoulder pitch joints were operated with the software and electronics described earlier. The software successfully coordinated the motions of the elbow and shoulder joints to keep the tip of the bucket on a straight line path to the coordinate selected. The arm moves slowly (average step rates of  $\sim 5$  PPS) at this point in development so that it stays on course. Repeatability of the tip position at a distance of 1.85 m from the shoulder was measured to be an average of 6 mm. Performance was optimized over a period of a week, and with more work the arm speed and accuracy can be drastically increased. However, we feel as though it meets the design requirements with its present performance.

### Lifting and Digging

The arm was tested for nominal strength requirements by commanding the arm to perform certain simple tasks. It was somewhat of a success to have the arm lift its own weight in a 1 G environment in a controlled manner. The arm was able to do this consistently in all poses. The arm's total deflection with loads when fully extended in 1 G was measured and is summarized in Figure 15.



**Figure 15. Measured Deflection When The Arm is Fully Extended Horizontally.**

The arm was able to provide a 20 N force in a vertical downward direction in the horizontal pull direction. The arm also successfully dug a trench 20 cm long by scooping 5 cm deep with each successive pass. The arm was commanded to lift a 1 kg weight and move it 1.5 m along the table top. Although the arm started out 5 cm off of the table and at 1.5 m was 3 cm off of the table due to deflections in the composite tube, this test was also very successful. The arm was able to perform all of these tests a number of times consistently, and without any noticeable strain to any of the systems electrical or mechanical components. These tests were also video taped for documentation and further analysis. Upon completion of the testing the joints were disassembled and inspected for wear. The shoulder pitch joint had performed about 70 cycles of 90° movements and the elbow pitch joint had performed about 100 cycles with about 30 of the cycles performed in the cold temperatures. Some wear could be seen on the harmonic drives teeth, and the pinion on the step motor, but this appeared to be minor and normal wear considering the dry lubrication. No unusual wear was noted.

## **Conclusions**

### **Performance**

Although we are pleased with the wrist and end effectors ability to measure soil properties and function in the Martian environment, the following known short comings of the system should also be mentioned: 1) The system requires higher current and more power than expected; 2) Although there is some mass savings by using the shape memory muscles for actuation it is not nearly as much as was originally believed - perhaps because of a lack of understanding of the additional components necessary to enable the muscle system to work efficiently; 3) Control has always been seen as a challenge for the shape memory devices, however in light of the minimal mass savings provided by shape memory it is apparent that small motors could produce much greater positioning control for nearly the same mass; 4) The wrist grasping mechanism could not be made reliable - the system gained too much complexity as it was developed despite efforts to keep it simple; 5) The wrist joint is tightly packed with small parts and screws as small as UNC 0-80, making assembly tedious and time consuming.

The composite tubes used for the limbs worked very well, providing excellent stiffness for very low mass. Improvements which need to be made include: 1) Part 11640 is not strong enough, and contributes to much of the deflection and spring in the arm; 2) The composite tube mounting system was also not stiff enough as well as being heavy; 3) The clamping sleeves used to fasten the composite tubes to the joints were used because of their ease in assembly which would help facilitate debugging of other systems. For an increased cost a composite mounting system can be designed which can save significant weight and increase stiffness.

The elbow and shoulder pitch joints performed very well. Their designs allowed for much easier assembly, and their adjustability helped insure smooth operation. The joints worked as the design intended, with 2 exceptions which were temporarily fixed before the testing took place. The problems are: 1) The Circular Spline Mounts (part 11500 and 11600) did not retain the Circular Spline adequately in the axial direction; 2) The input shaft to the harmonic drive was not retained axially which allowed the wave generator to walk inward on the Flex Spline; 3) Brakes were not needed for the most part as the arm joints were only backdrivable occasionally without the brakes, when the arm was held horizontally in a fully extended position.

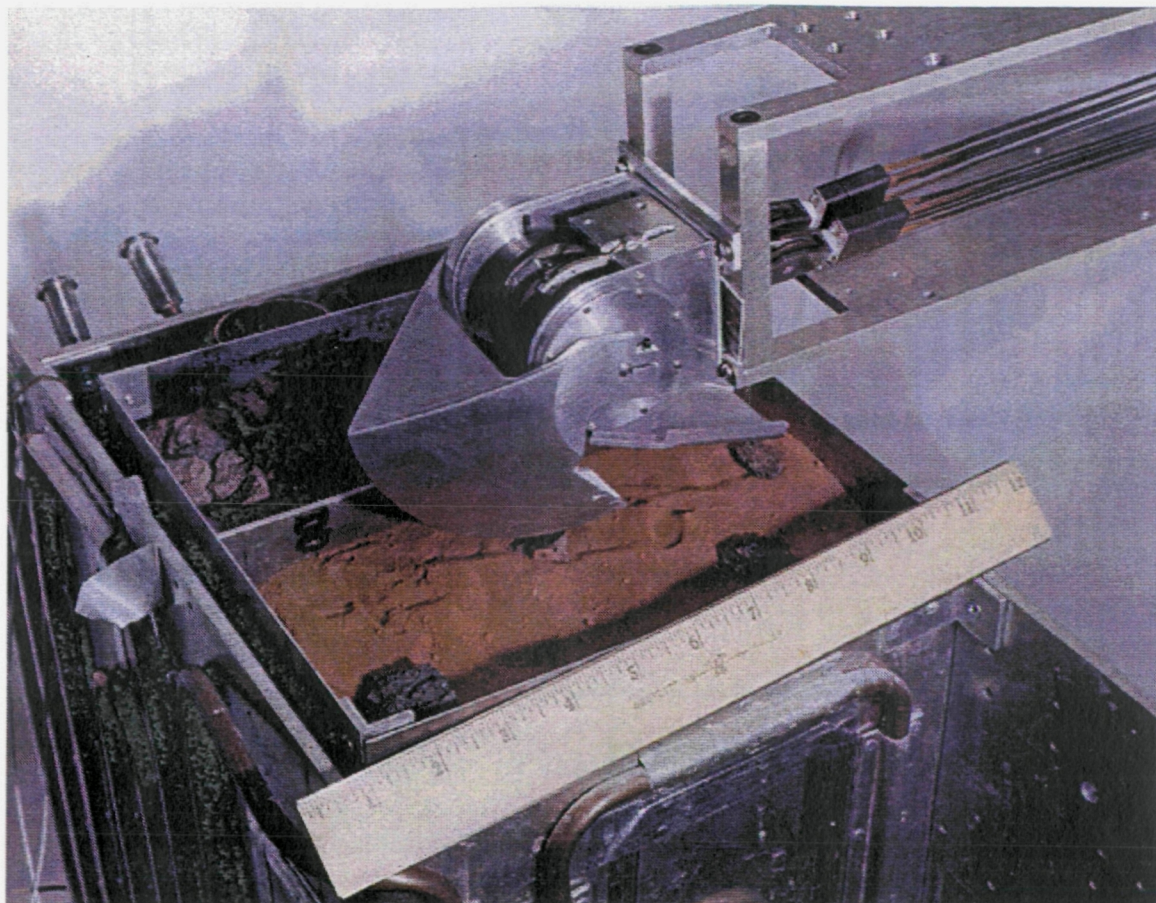
### **Upgrades for Flight Missions**

The elbow and shoulder pitch designs would need little modification to be made ready for an actual mission. The bearings, seals, step motor, and resolver all have flight heritage. Harmonic drives also have extensive flight heritage, though we used the new "S tooth" design produced by HD Systems because of its lower spring rate. The step motor hybrid and resolver-to-digital IC's can also be qualified for space flight. Wrist mechanisms with shape memory muscles would be much more difficult to qualify for space flight.

Considerable mass savings can be realized for a small increase in fabrication costs. Composite tube mounting is one example mentioned previously. Another is thinner wall thickness and lighting holes can be called out on many of the machined steel parts which would still be affordable for a flight program.

The arm tested weighs 4.2 kg and has 3 DOF. With a similar effort put into a shoulder azimuth joint the 4 DOF lab version would have weighed 5.5 kg. A 4 DOF flight arm with a reasonable amount of mass savings over the lab unit is estimated to weigh 4.4 kg. Further mass savings can be achieved by testing the arm in a 0.38 G facility, using constant tension wires and counter balances to keep the full gravity of Earth from damaging a weaker arm. This would add significant costs to the program. However, it would be possible to use the elbow mechanism developed on this contract with a size 15 step motor for the shoulder pitch joint in 0.38 G. A smaller elbow could be designed around a size 14 harmonic drive that would also be adequate for 0.38 G. With this scheme a 4 DOF arm for Mars would weigh 4.1 kg, and a 3 DOF arm would weigh 3.2 kg.



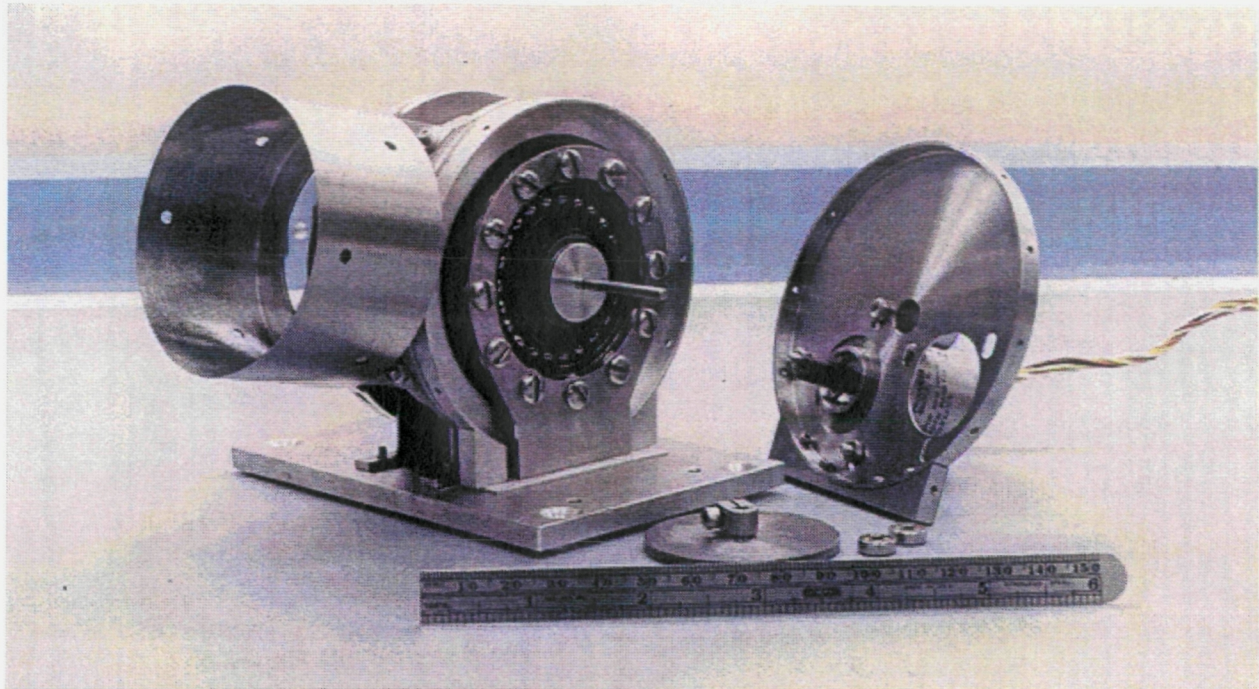


**Color Figure A1 (Top).** SAID Wrist Assembly mounted for testing. The housing cover has been removed to show the rap spring triggers and brakes. Shape Memory Muscles are visible extending out of the picture on the right side.

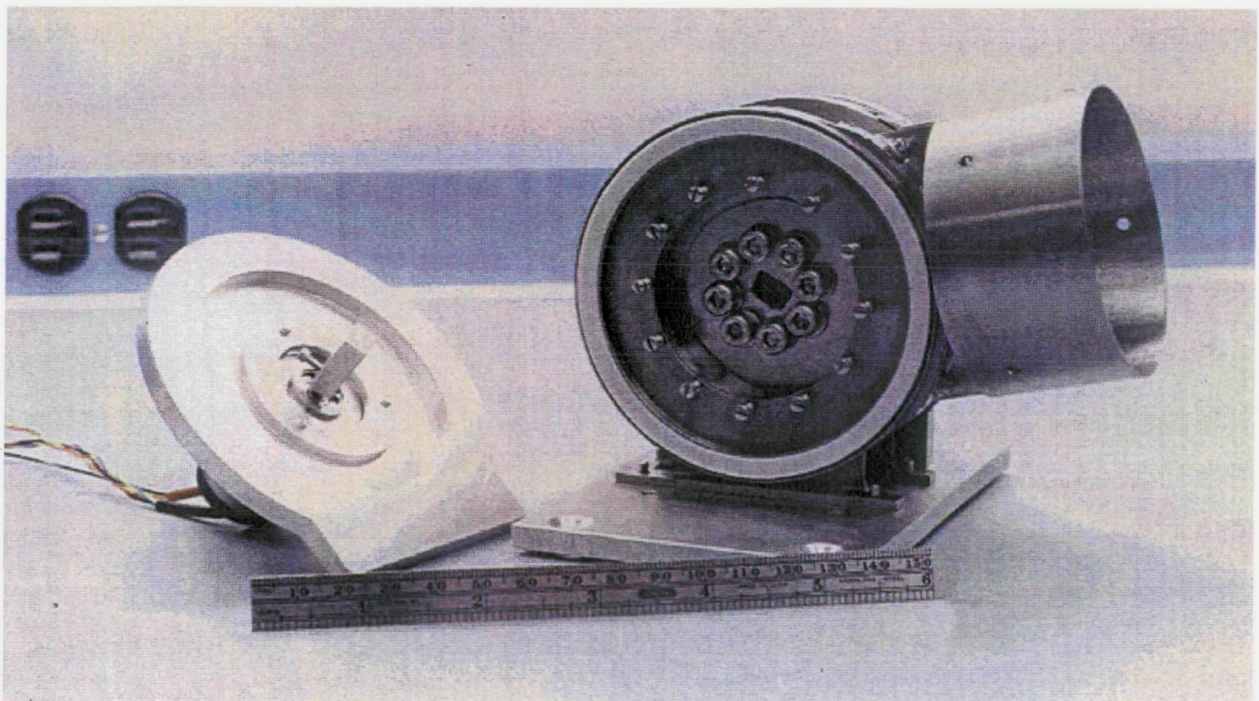


**Color Figure A2 (Left).** Wrist assembly with cover installed and a composite tube housing the Shape Memory muscles.



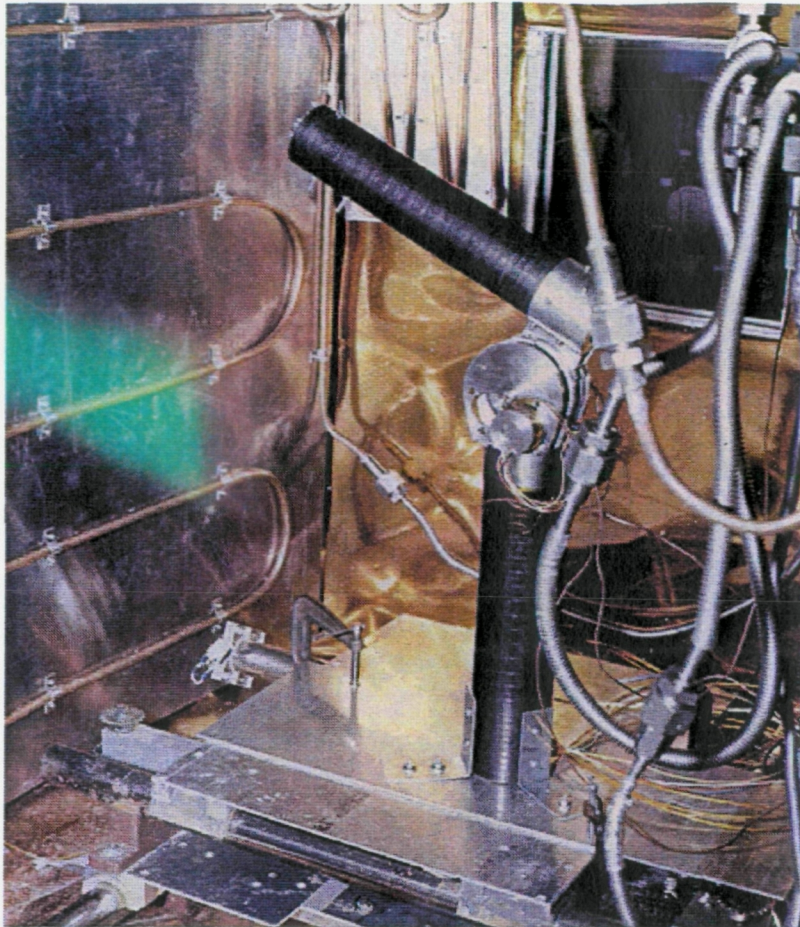


**Color Figure A3.** Right side of shoulder pitch joint with motor mount, spur gear and bearings removed. The wave generator ball bearings in the harmonic drive are visible. Other harmonic drive elements appear dark because of the sputtered dry lube coating.



**Color Figure A4.** Left side of shoulder pitch joint with resolver and its mount removed. The Teflon seal can be seen in its gland just inside the outer diameter of the joint. A square key is used to connect the resolver to the harmonic drive output.



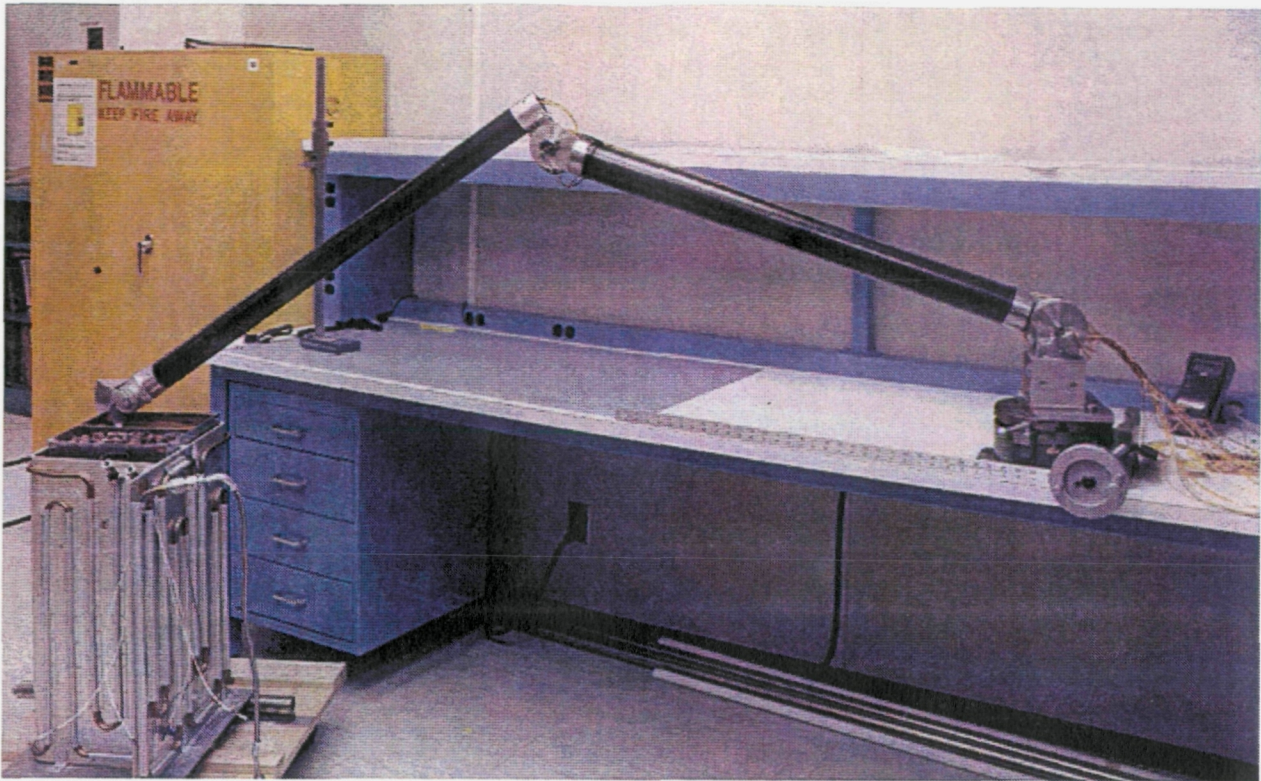


**Color Figure A5.** Vacuum chamber set-up for elbow pitch joint environmental testing. 2 kgs of Lead are bolted into the end of the short forearm tube to provide a load. The joint performed well in the 6 mb atmosphere at temperatures down to  $-80^{\circ}\text{C}$ . A video camera recorded the cycles through the window in the back of the chamber.

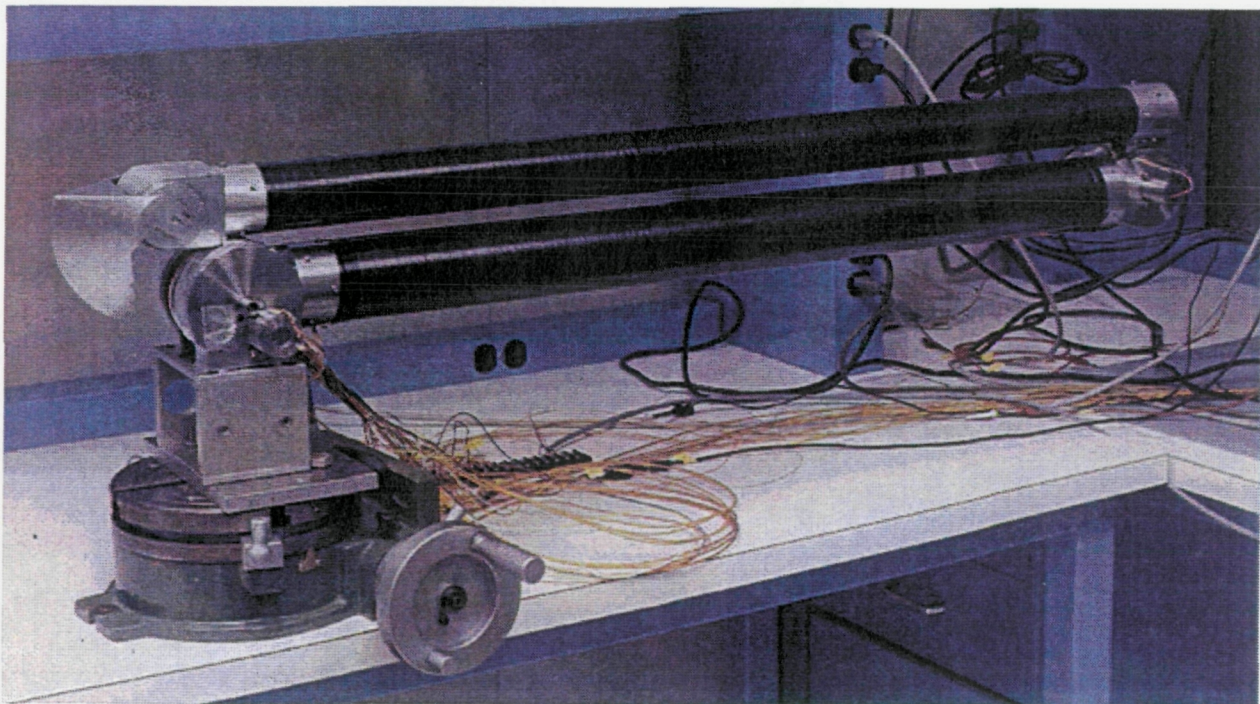


**Color Figure A6.** SAID fully assembled with completed cabling, electronics, and software control. The system's software coordinates the joint motion to keep the tip of the arm on a straight line path to the selected coordinates. Operation on Mars will require this level of intelligence because of the 5 to 40 minute time delay in communications.

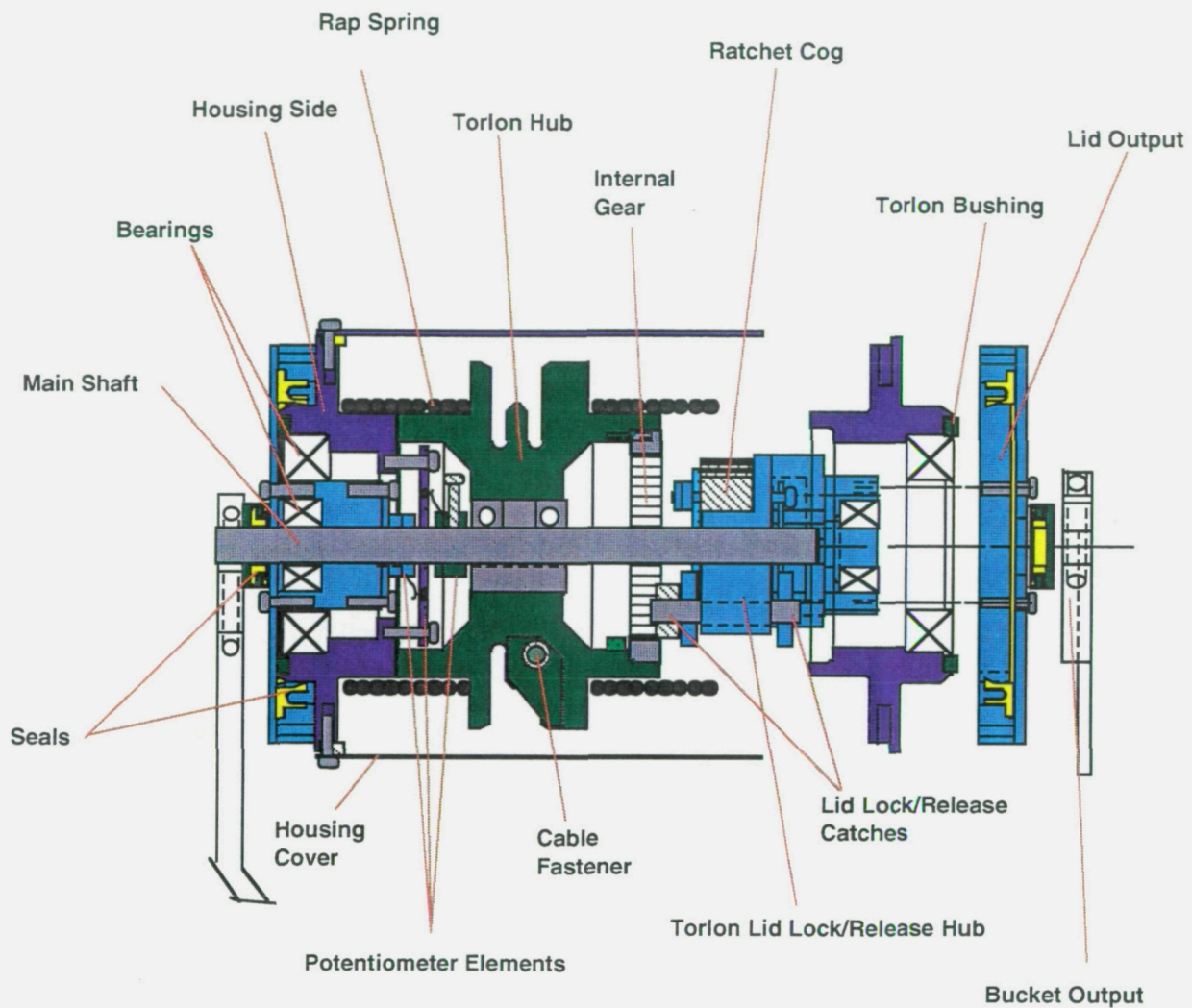




Color Figure A7. SAID arm fully extended can reach 2 meters.

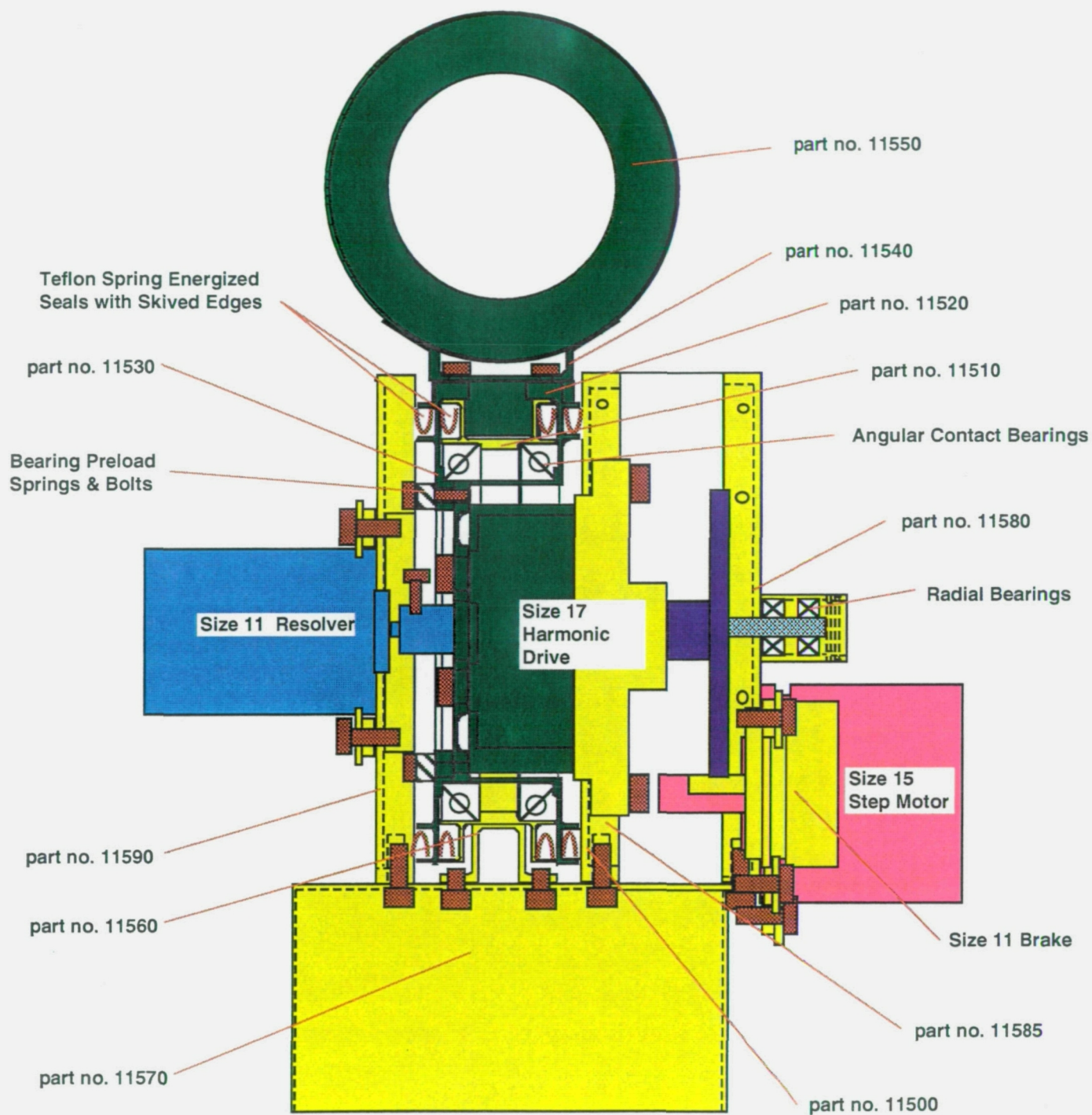


Color Figure A8. SAID arm in the stowed position.

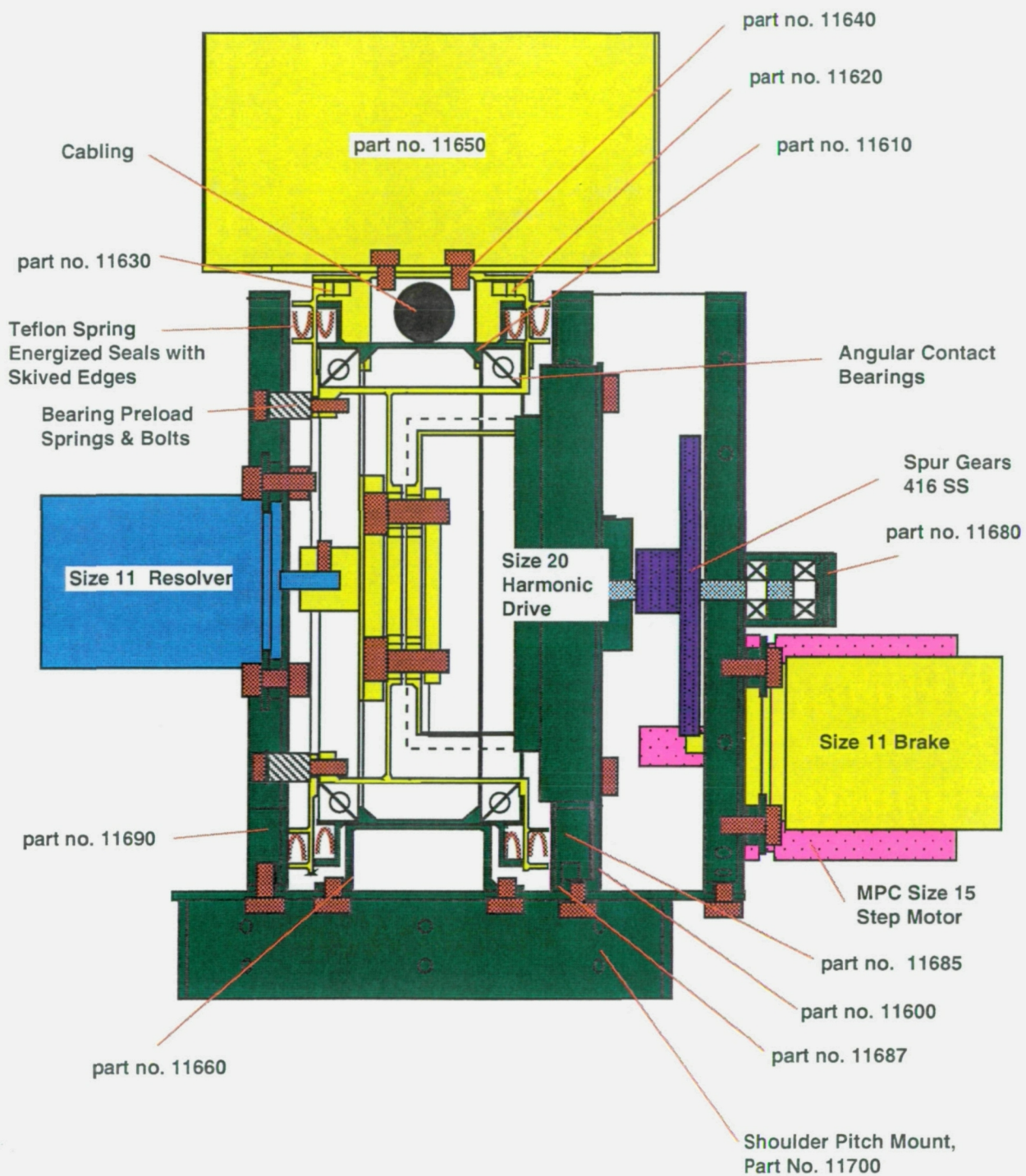


*Color Figure A9. Cross Section of SAID Wrist Mechanism*



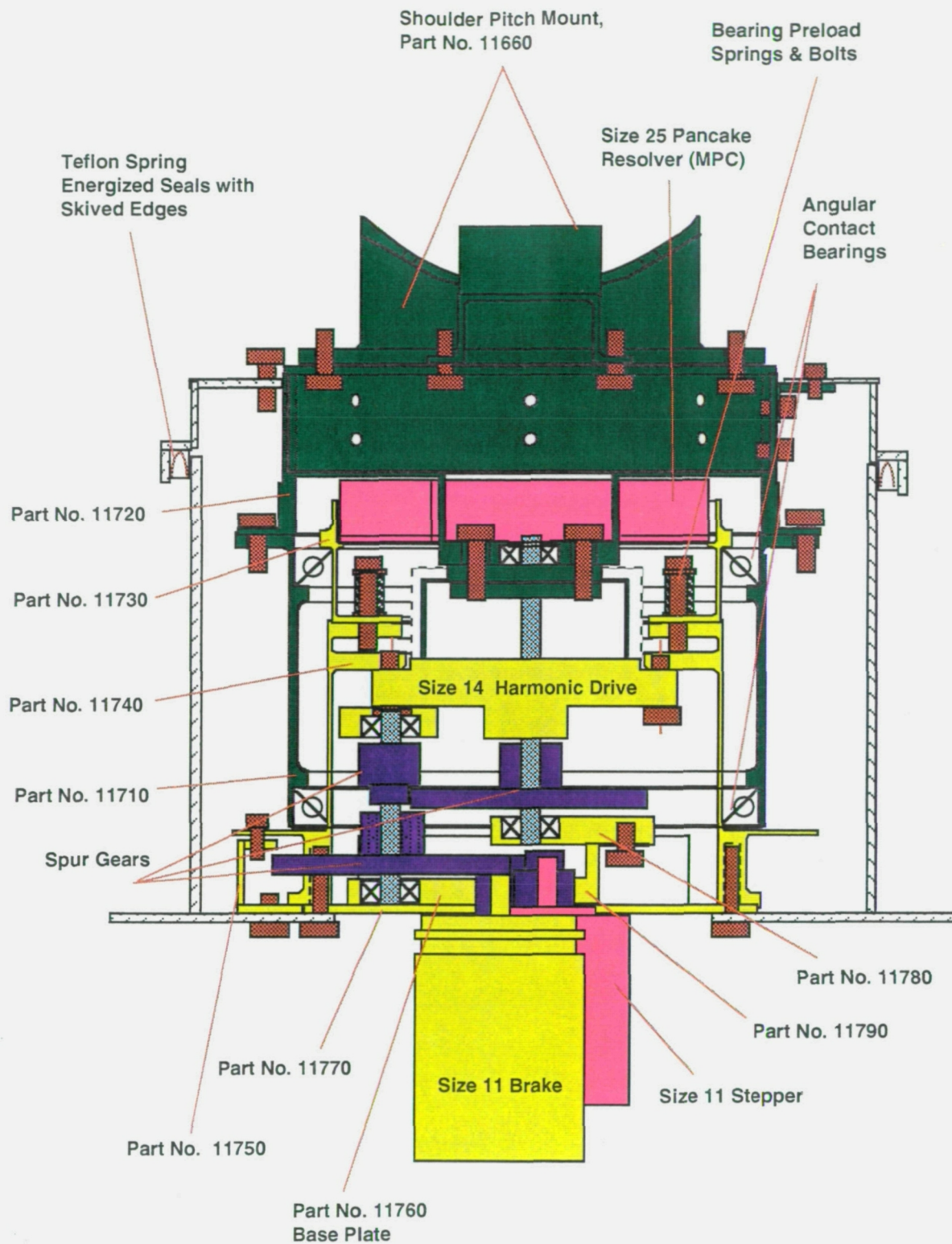


Color Figure A10. Cross Section of Elbow Joint



Color Figure A11. Cross Section of Shoulder Pitch Joint.





*Color Figure A12. Cross Section of Shoulder Azimuth Joint*

## REPORT DOCUMENTATION PAGE

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| 13. ABSTRACT<br><br>This report details the progress for contract NASW-4818, Sample Acquisition and Instrument Deployment (SAID), a robotic system for deploying science instruments and acquiring samples for analysis. The system is a conventional 4 degree of freedom manipulator 2 meters in length. A baseline design has been achieved through analysis and trade studies. The design considers environmental operating conditions on the surface of Mars, as well as volume constraints on proposed Mars Landers. Control issues have also been studied, and simulations of joint and tip movements have been performed. The systems have been fabricated and tested in environmental chambers, as well as soil testing and robotic control testing. |                                                             |                                                            |                                                                              |
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